In-band full-duplex wireless

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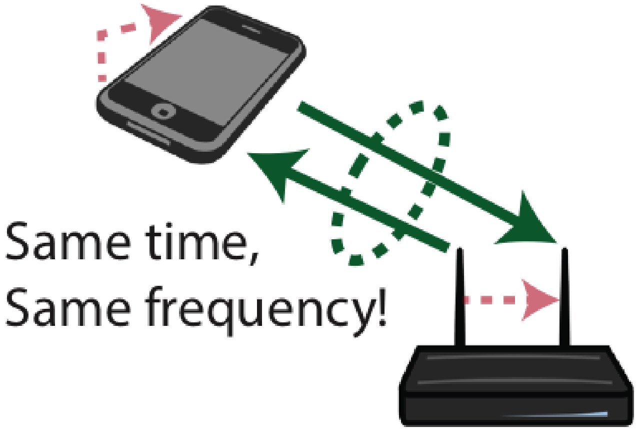
Outline

- Introduction to Full-Duplex Wireless
- Motivation
- Challenges
- Topologies
- Design of an SI-cancelling receiver
- Characterization
- Conclusion

In-band full-duplex wireless

- TX and RX *simultaneously* at *same* frequency



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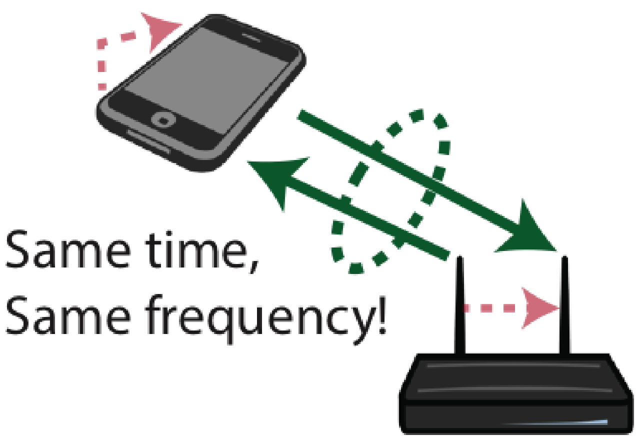
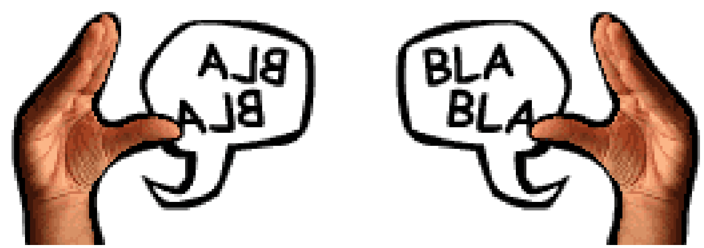
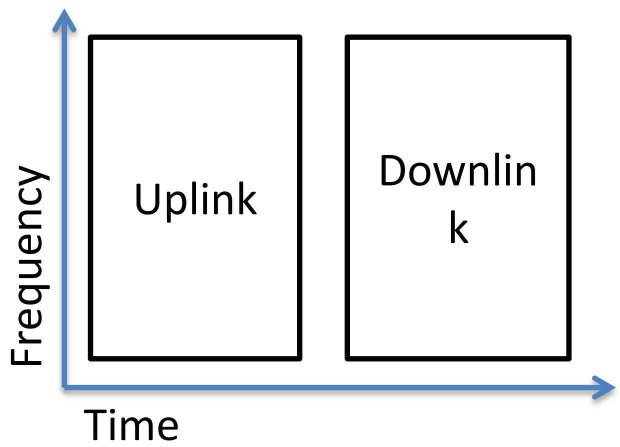




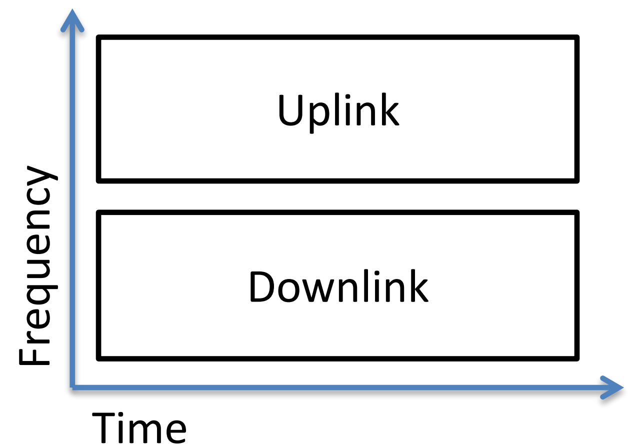
In-band full-duplex wireless

- TX and RX *simultaneously* at *same* frequency

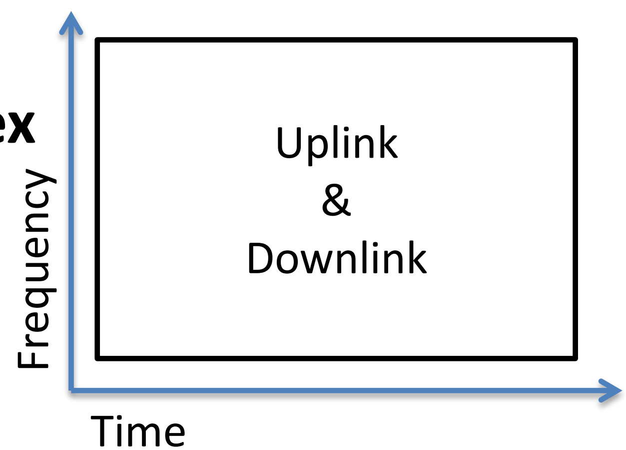
TDD



FDD



Full-Duplex



Note:
FD = duplexing scheme.
On top of this:
multiple access scheme
(TDMA, OFDMA, ...)

In-band full-duplex wireless

- TX and RX *simultaneously* at *same* frequency
- Why?
  - Up to 2x spectral efficiency

In-band full-duplex wireless

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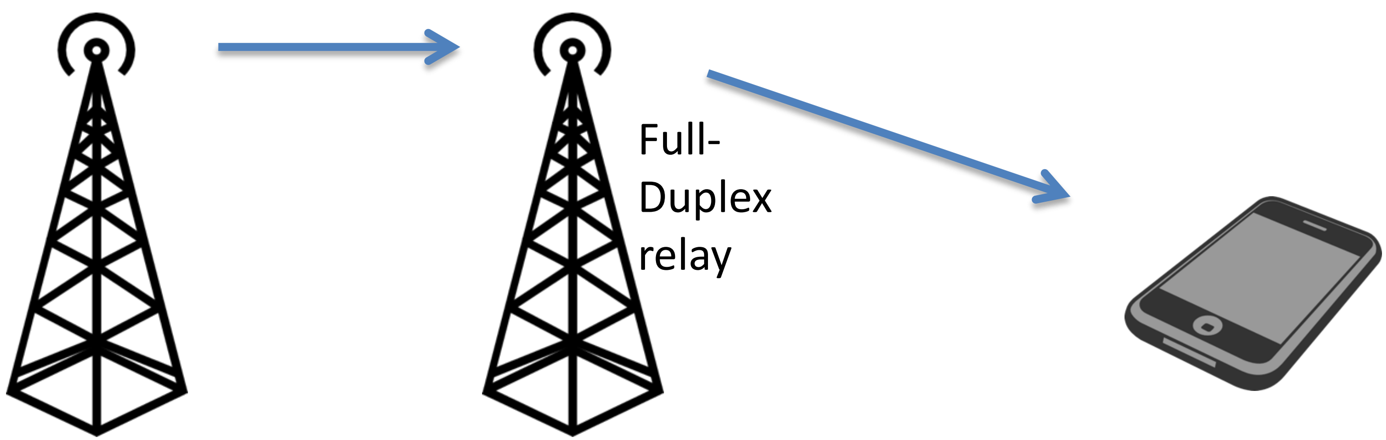
  - Simplified / flexible frequency planning

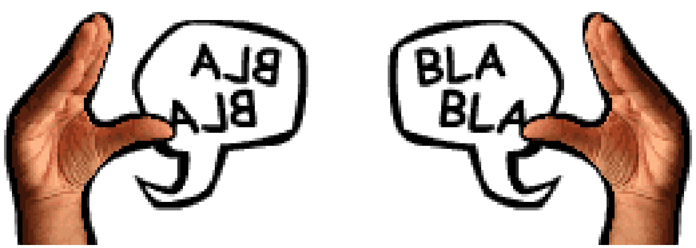
In-band full-duplex wireless

- TX and RX *simultaneously* at *same* frequency
- Why?
  - Up to 2x spectral efficiency
  - Simplified / flexible frequency planning
  - Reduced air interface delay (e.g. FD relaying)



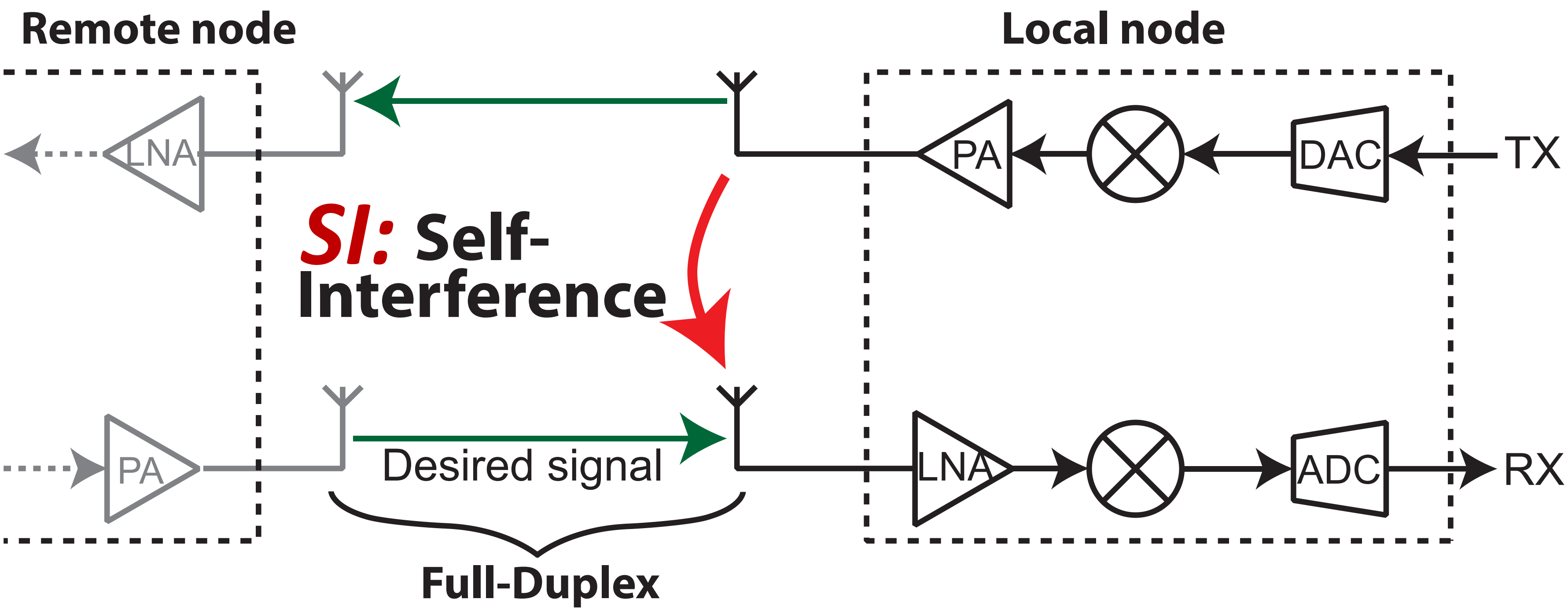
In-band full-duplex wireless

- Why not?



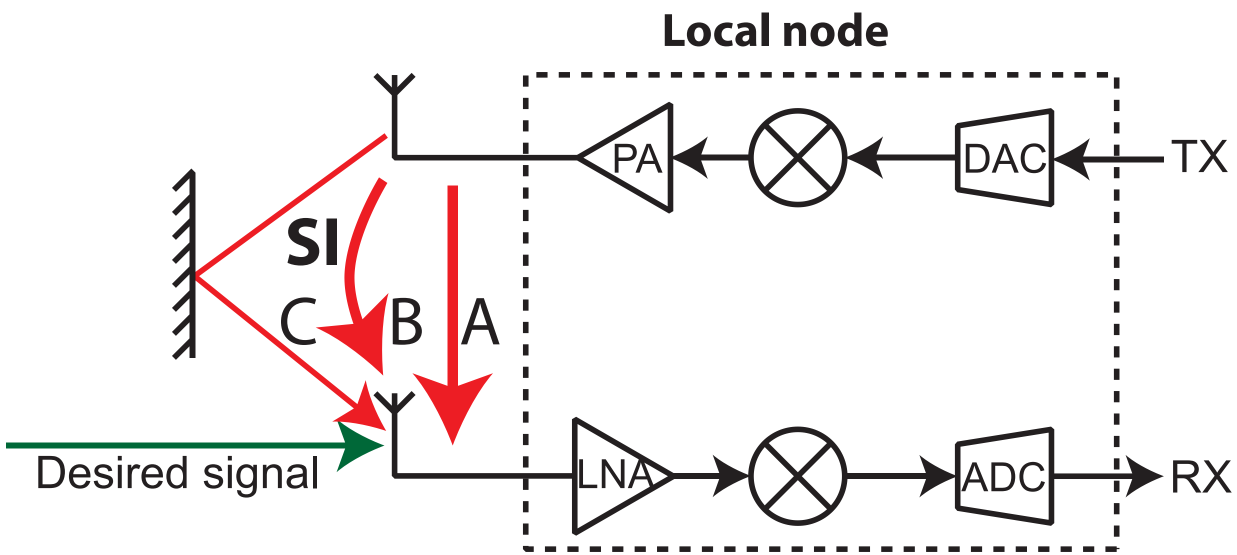
In-band full-duplex wireless

- Why not?



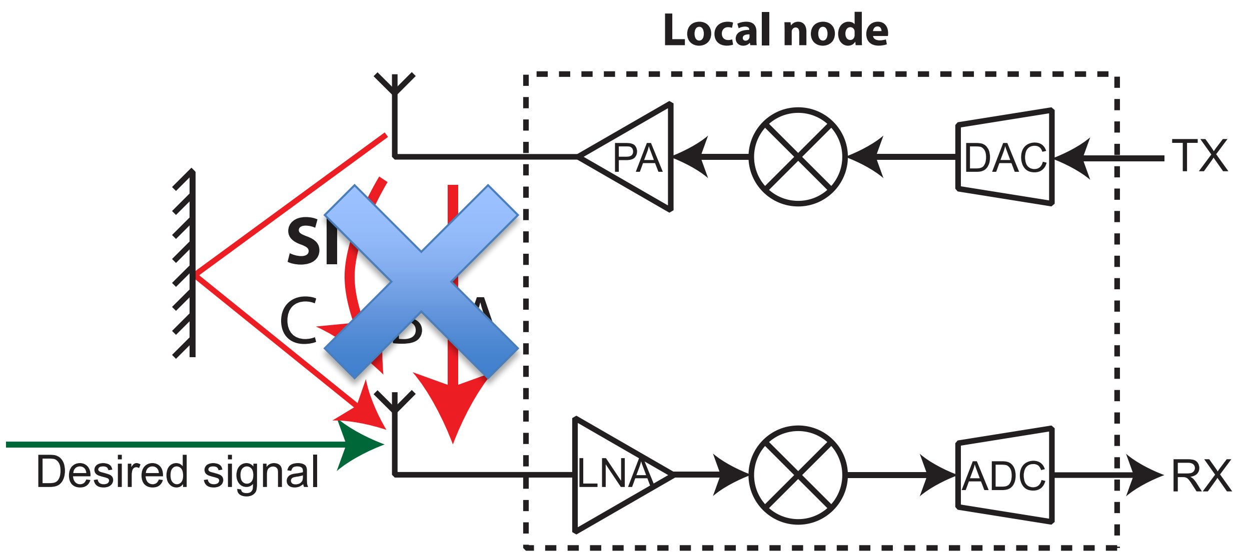
- P_{TX}: ~0..20dBm RX-Sensitivity: ~-100..-70dBm
- ⇔ ***70-120dB Self Interference Cancelling (SIC)!!***

Self-interference: A closer look



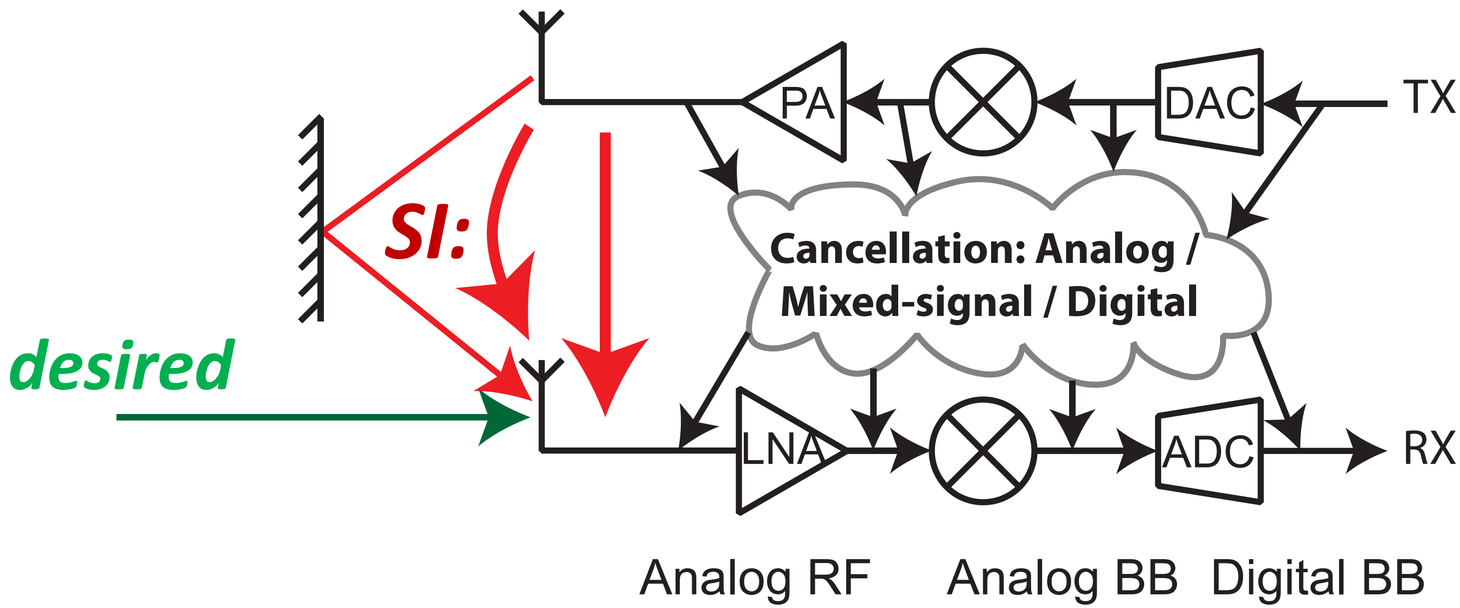
- A,B: Frequency-flat
- C: Frequency-selective (multi-path contribution may add up or cancel)

Self-interference: Isolation



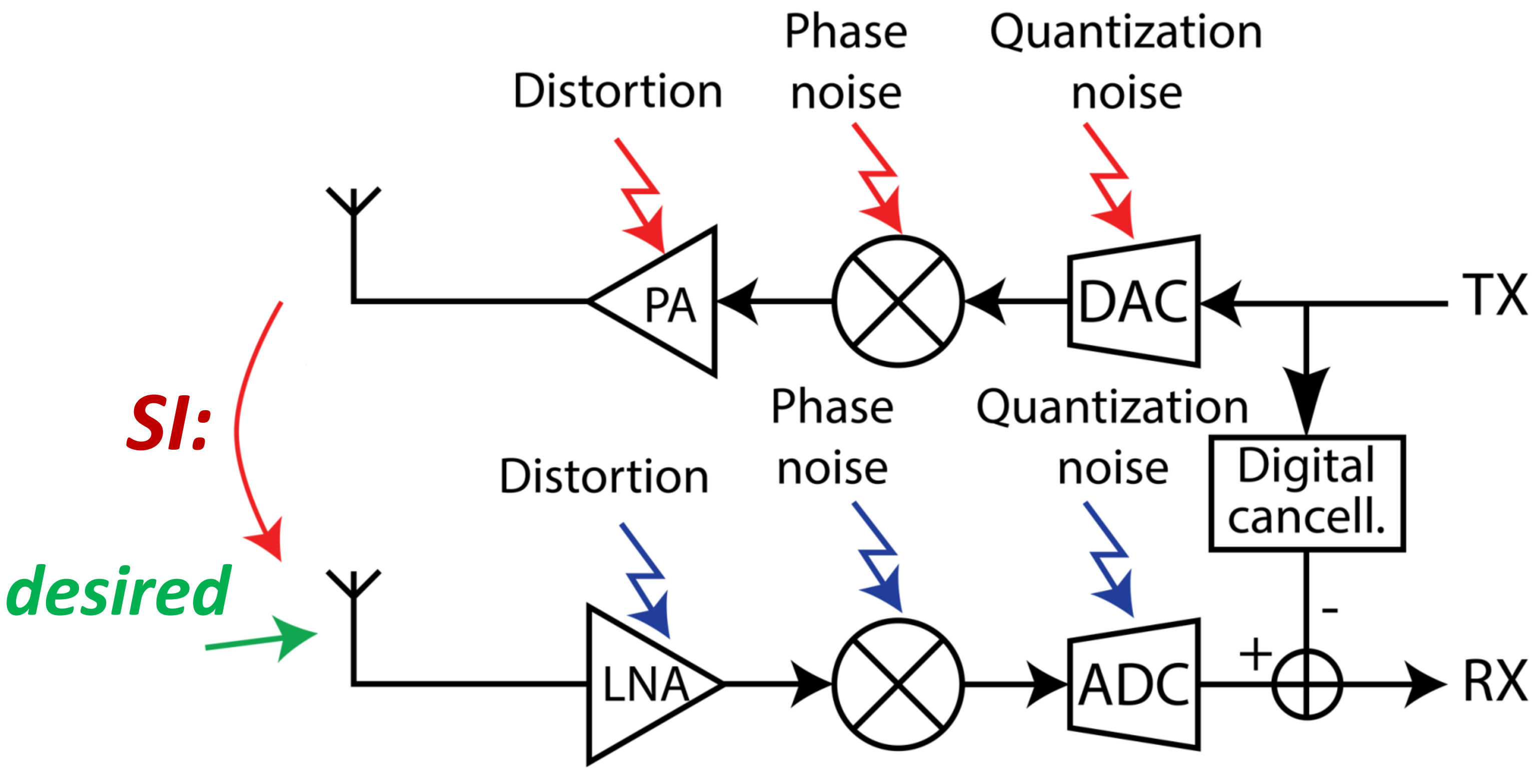
- Reduce crosstalk in RF domain:
  - Antenna spacing
  - Directivity
  - Polarization

Self-interference: Cancellation



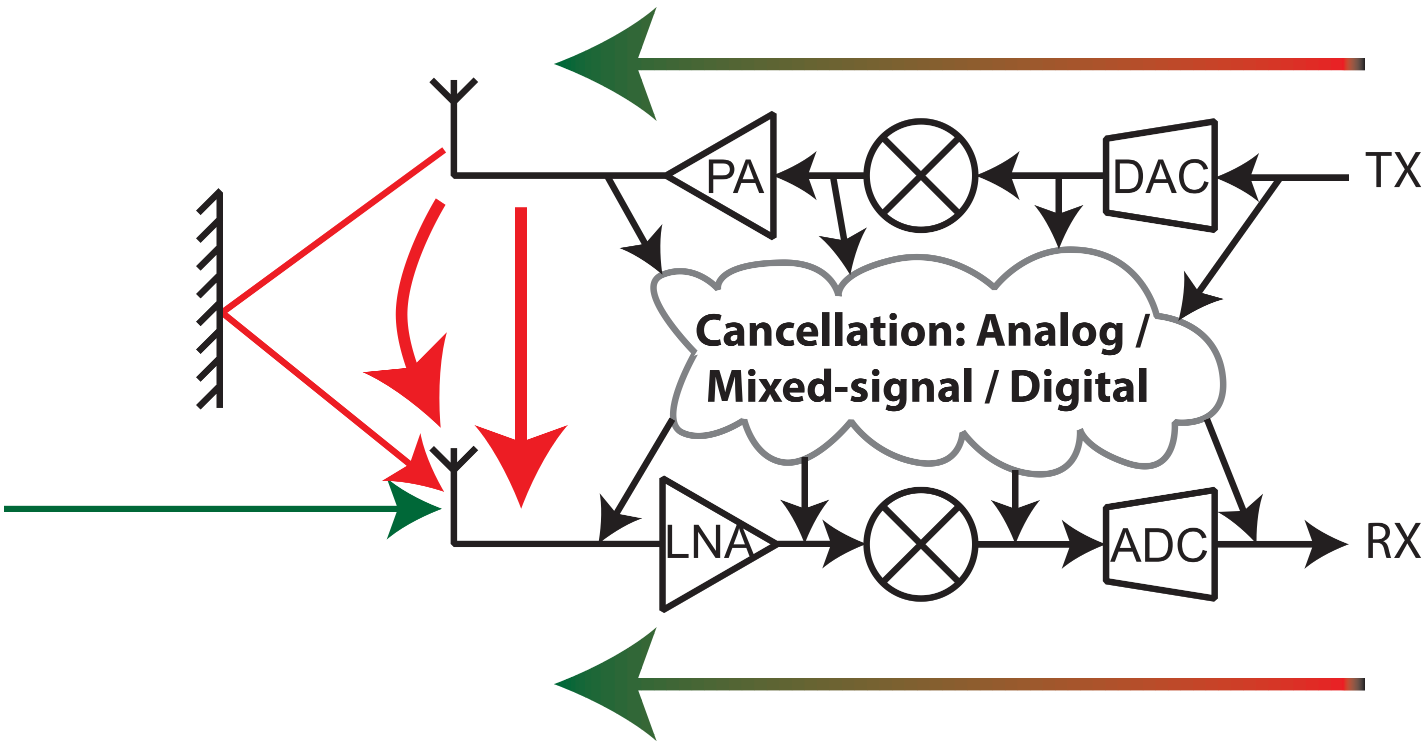
- Tap signal from TX path
- Modify
- Subtract from RX path

Digital-only SI-cancellation



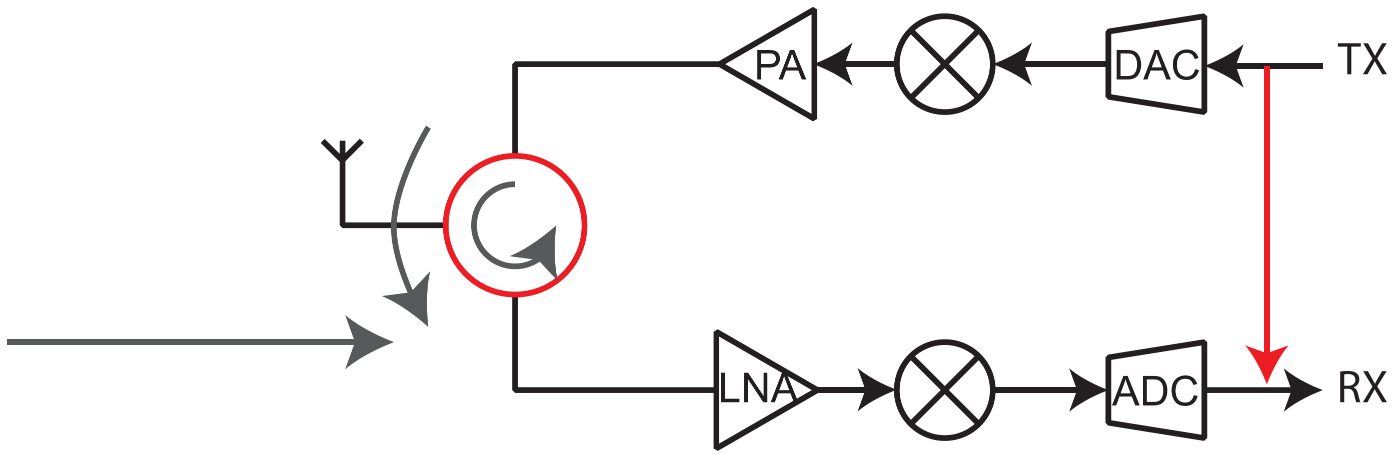
- Many TX/RX impairments affect SI
  - Some deterministic, some noisy
  - Digital cancellation can only cancel deterministic parts
  - ***Only Digital SI-Cancellation is NOT enough!!***

Self-interference cancellation



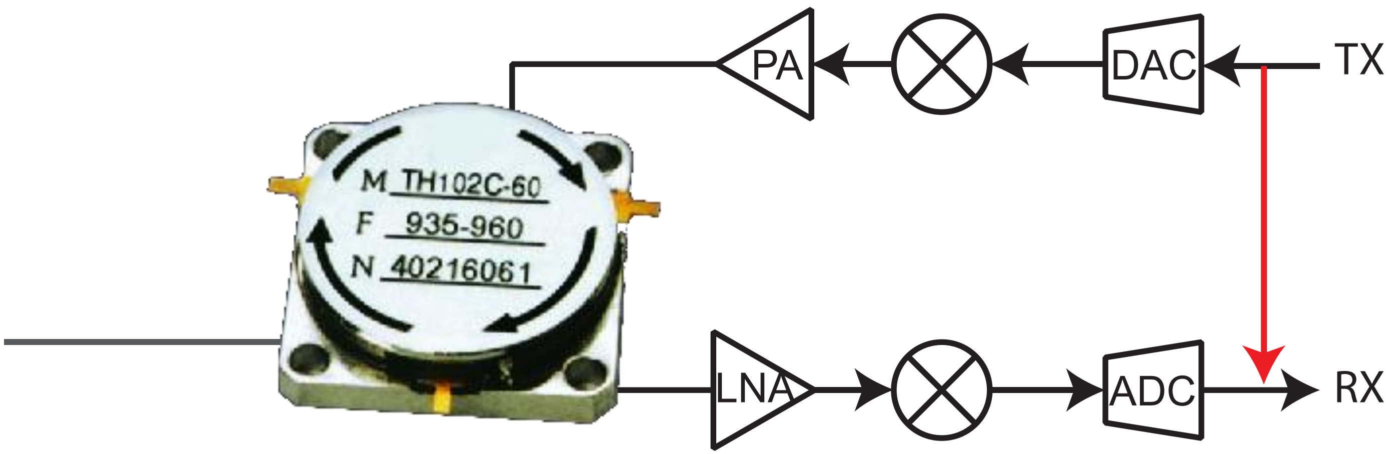
- **Need to combine cancellation in several domains!!**
- Digital but also mixed A/D and analog cancellation
- Closer to the antenna: more analog

SI-rejection: Circulator



- Single antenna solution
- Currently expensive, bulky components
- SI-rejection limited by antenna matching

SI-rejection: Circulator



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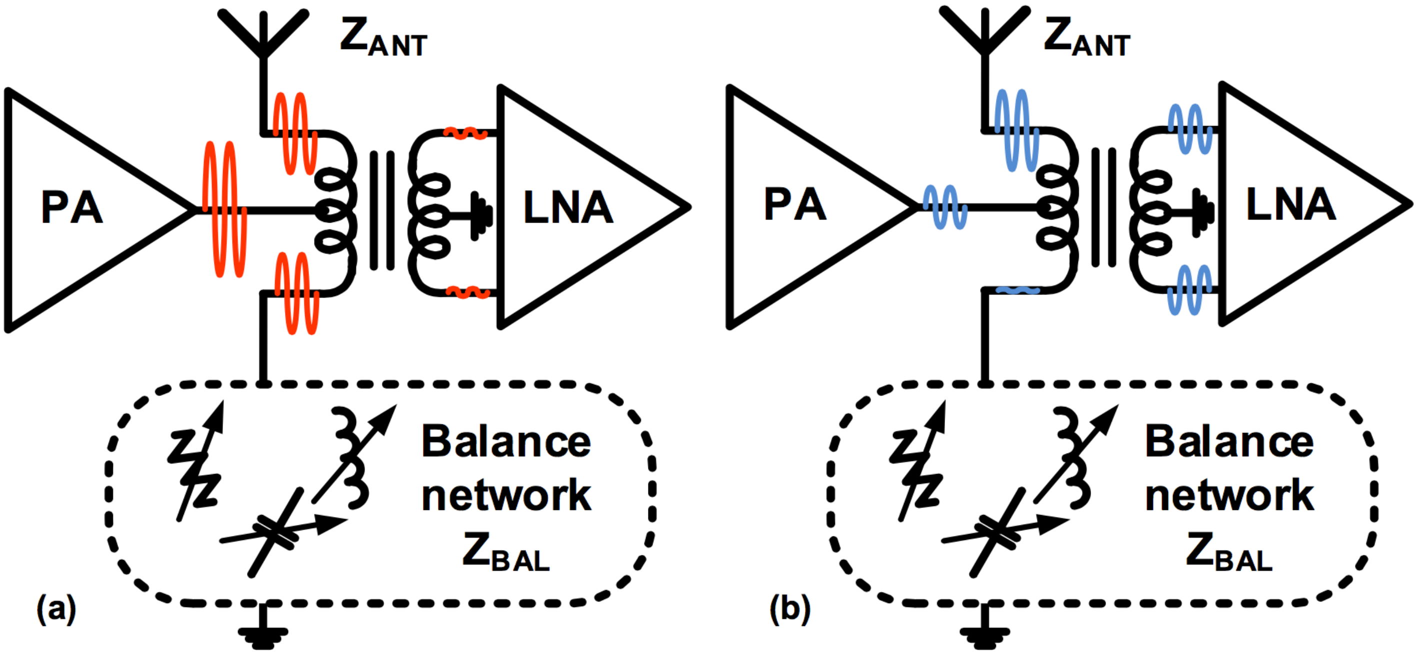
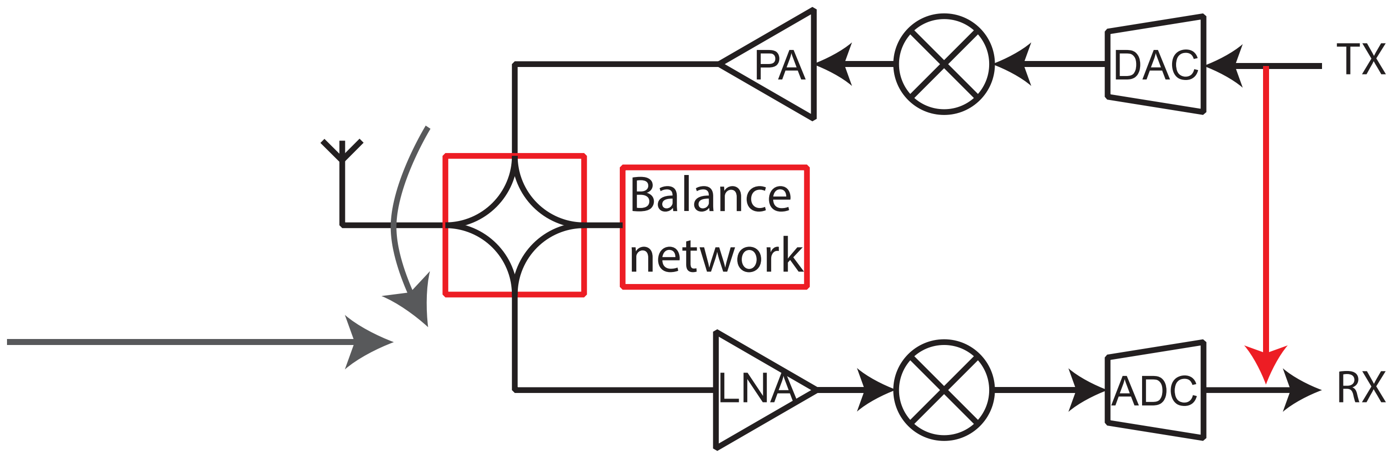
SI-rejection: Electrical balance duplexer



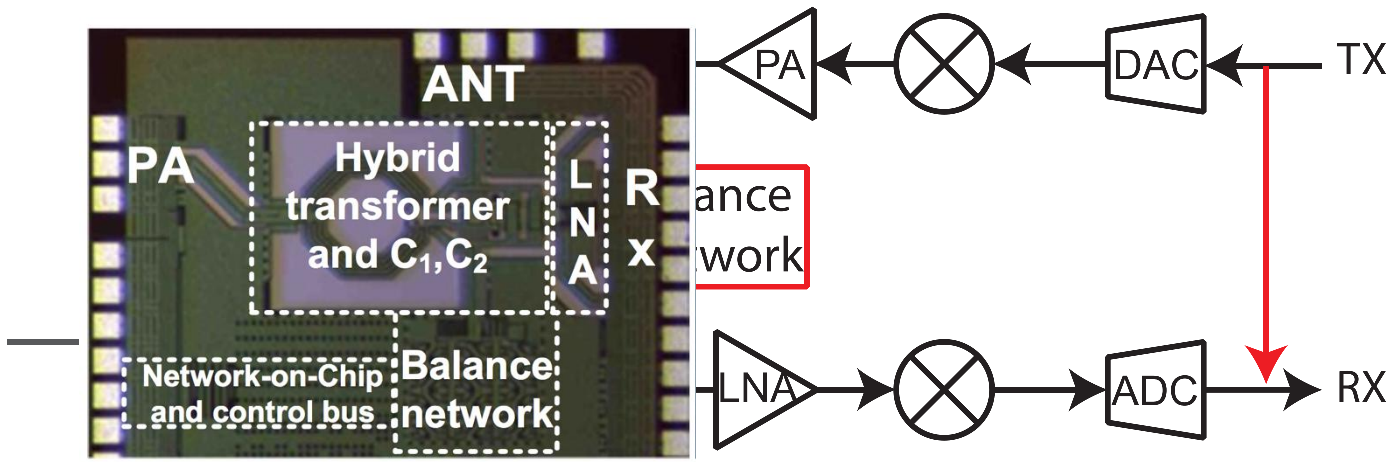
[vanLiempd, CROWNCOM2014]

SI-rejection: Electrical balance duplexer



- Single antenna solution
- High integration potential
- Tunable (adapt to changing environment)
- Reciprocal device: fundamental insertion losses
- Limited bandwidth of practical transformer
- Extreme linearity requirements balance network

SI-rejection:
Electrical balance duplexer



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[vanLiempd, CROWNCOM2014]

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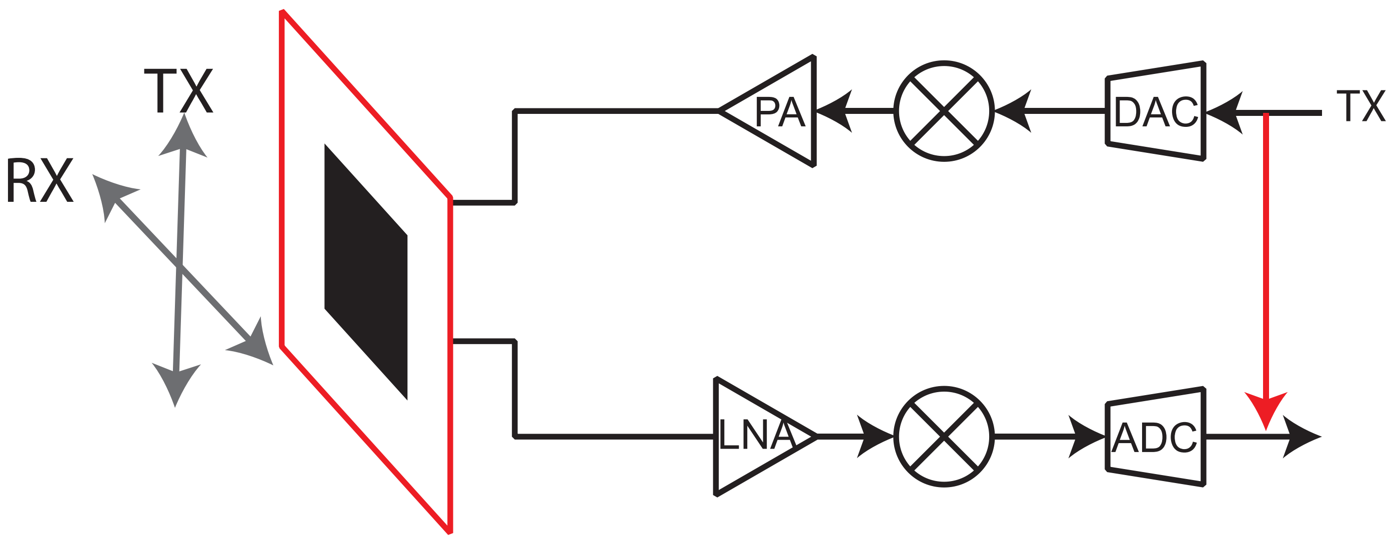
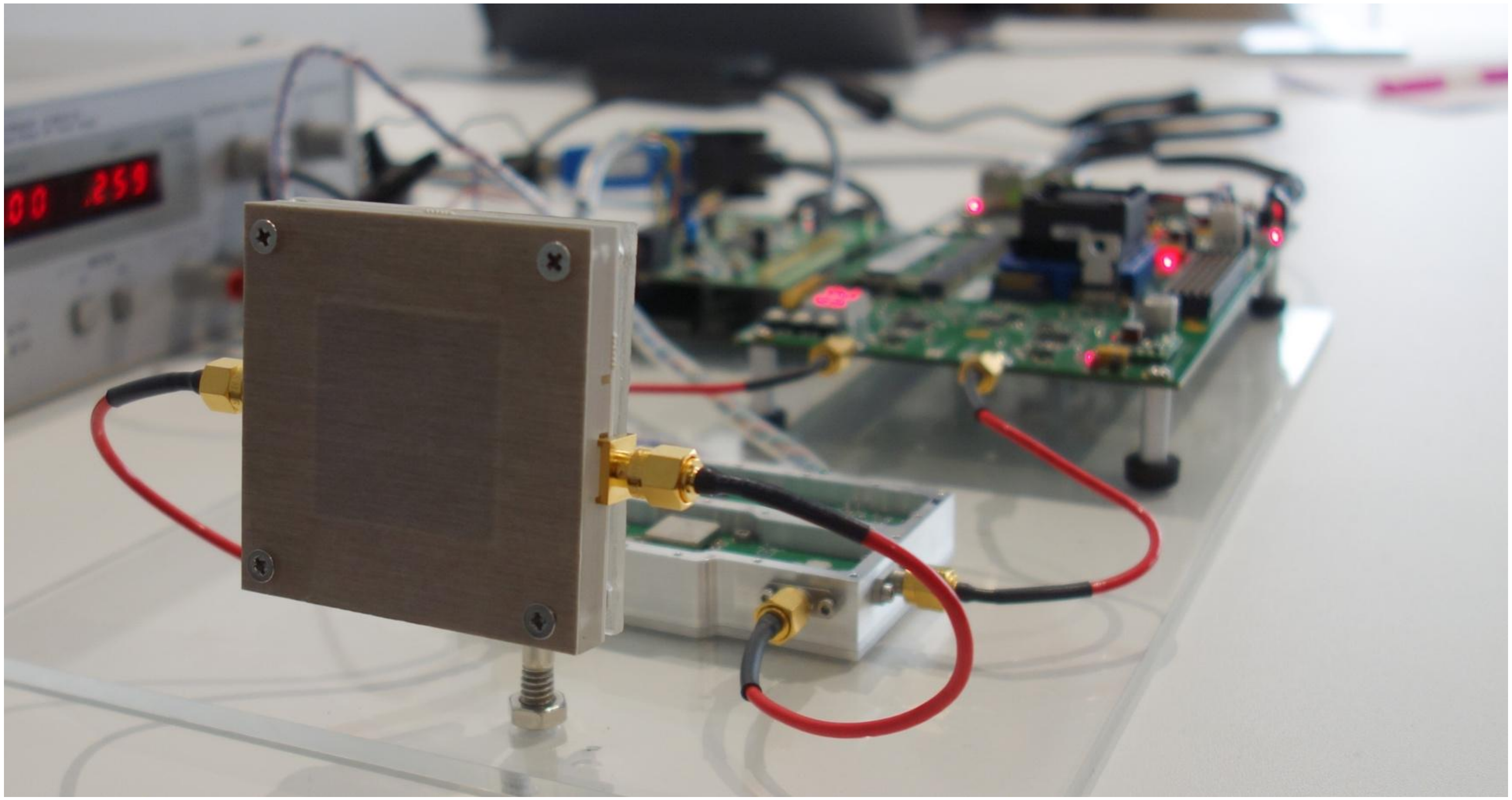
SI-rejection: Dual-polarized antenna



- High isolation
- High directivity (e.g. backhaul)
- Tailored for specific frequency

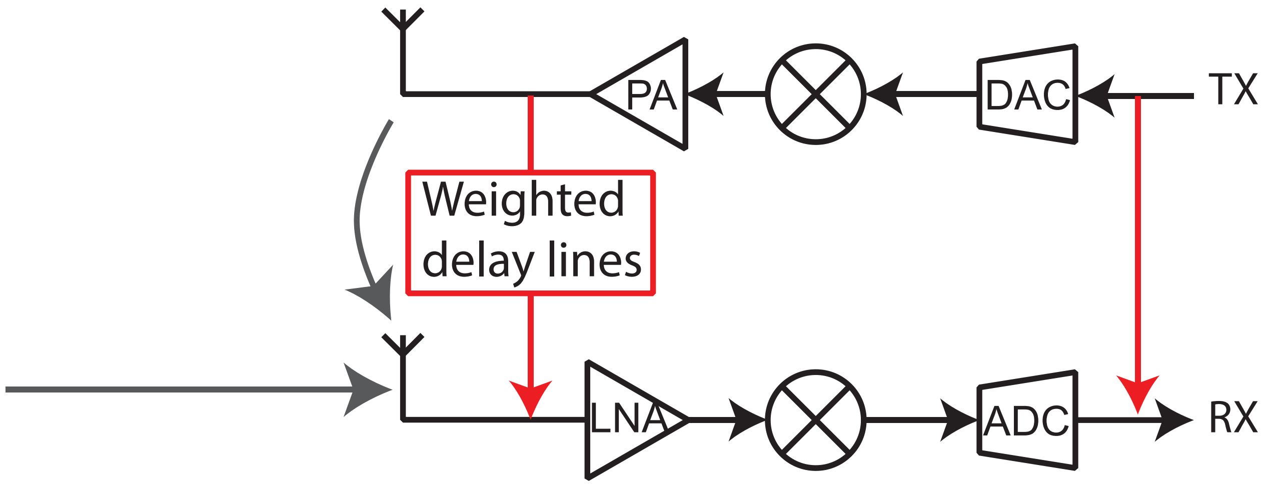
[Debaillie, VTC2015]

SI-rejection: Dual-polarized antenna



[Debaillie, VTC2015]

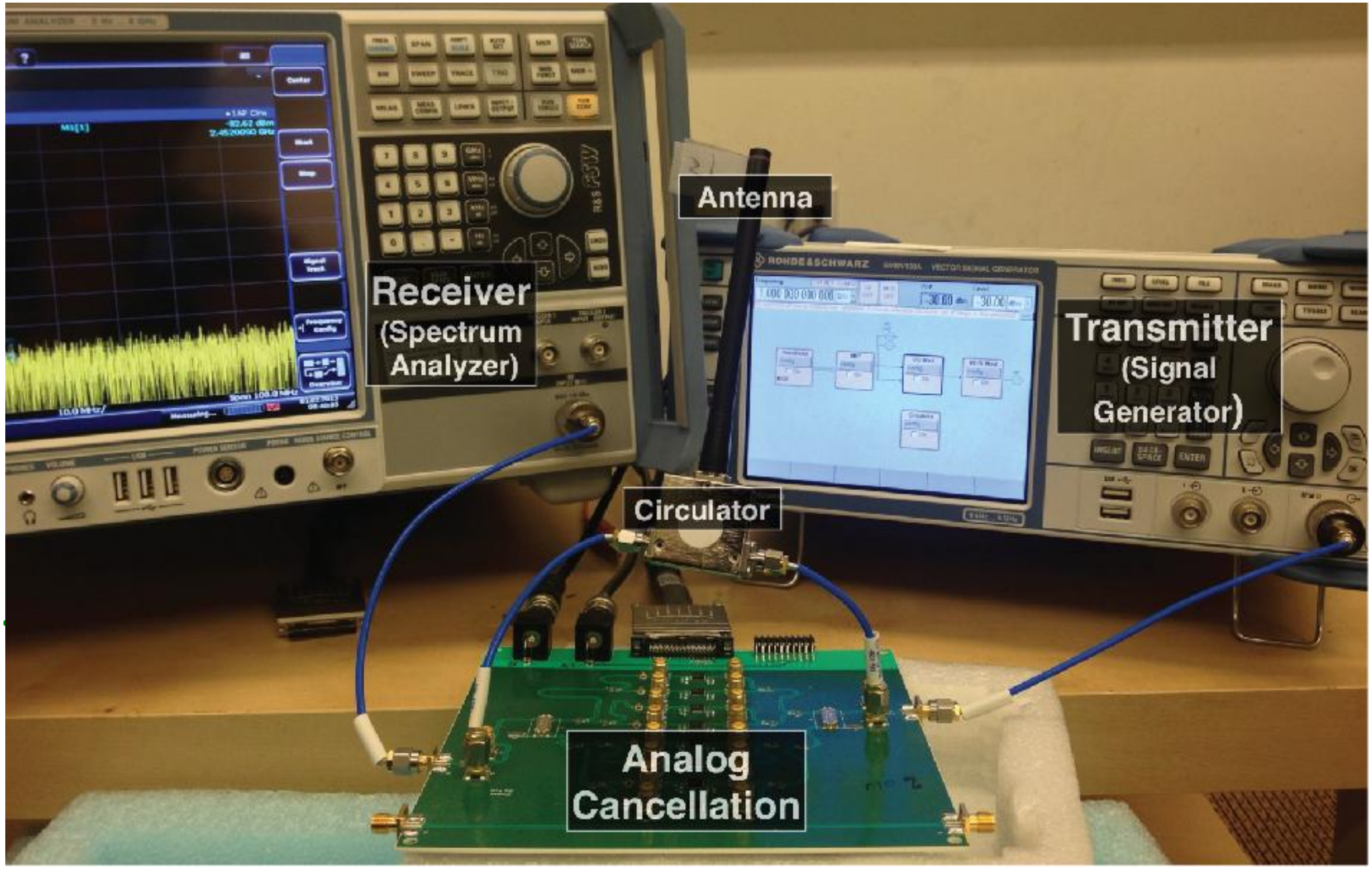
SI-rejection:
Analog FIR filter



- True time delay → Wideband cancellation
- Delay lines bulky

[Bharadia, Sigcomm2013]

SI-rejection:
Analog FIR filter



[Bharadia, Sigcomm2013]

Design of an Frequency Agile Highly Agile SI-cancelling receiver

[vdBroek, ISSCC2015]
[vdBROEK, RFIC2015]

(University of Twente, Enschede)

Antenna isolation

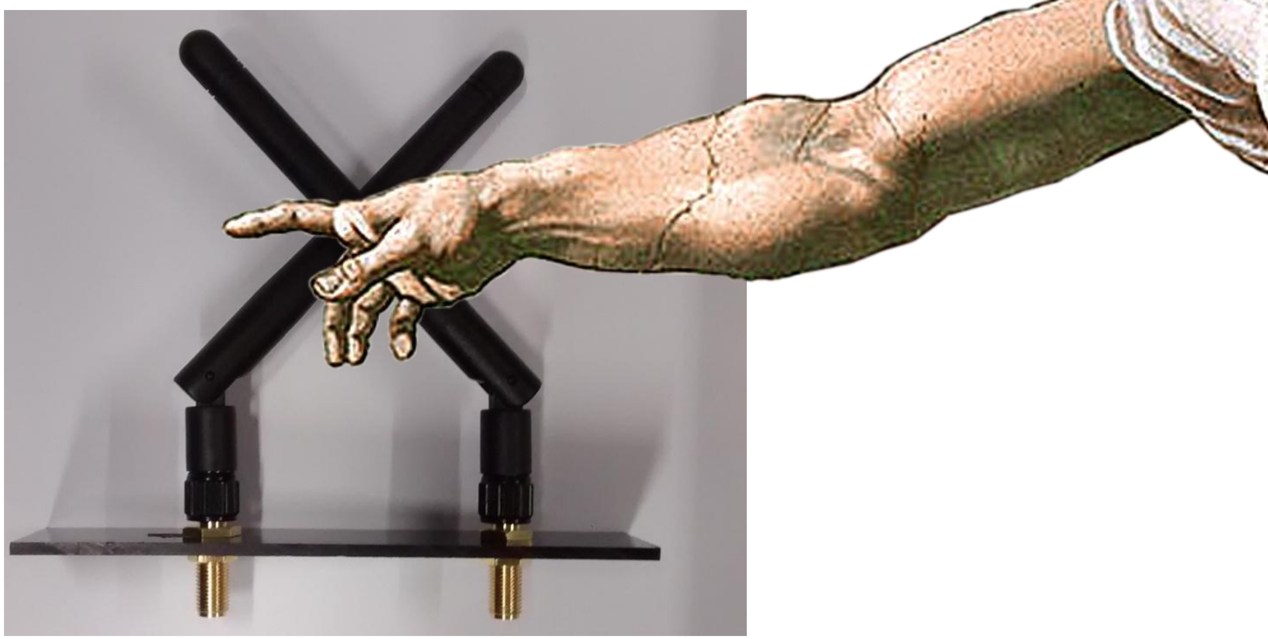
How much isolation do we achieve in hand-held devices?

Experimental:

Antenna isolation

How much isolation do we achieve in hand-held devices?

Experimental:



~20dB worst-case isolation

Antenna isolation

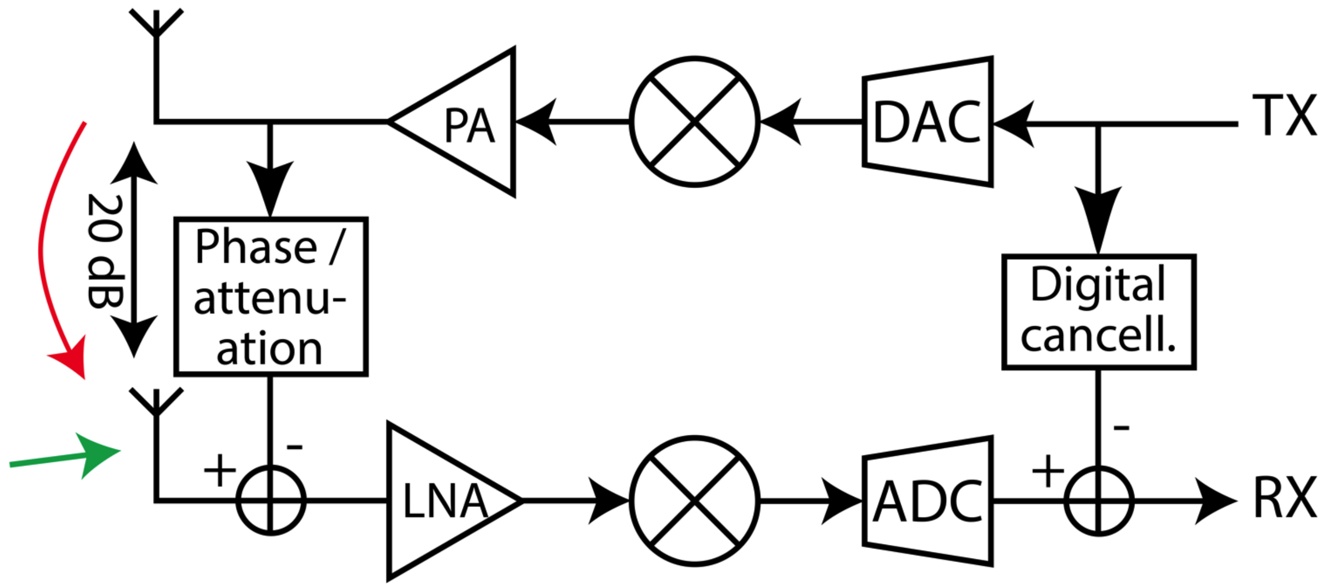
Strength of reflections?

- 2.45 GHz ISM band, reflective room:
  -40 to -50dB

[Everett, Tr. Wireless 2013]

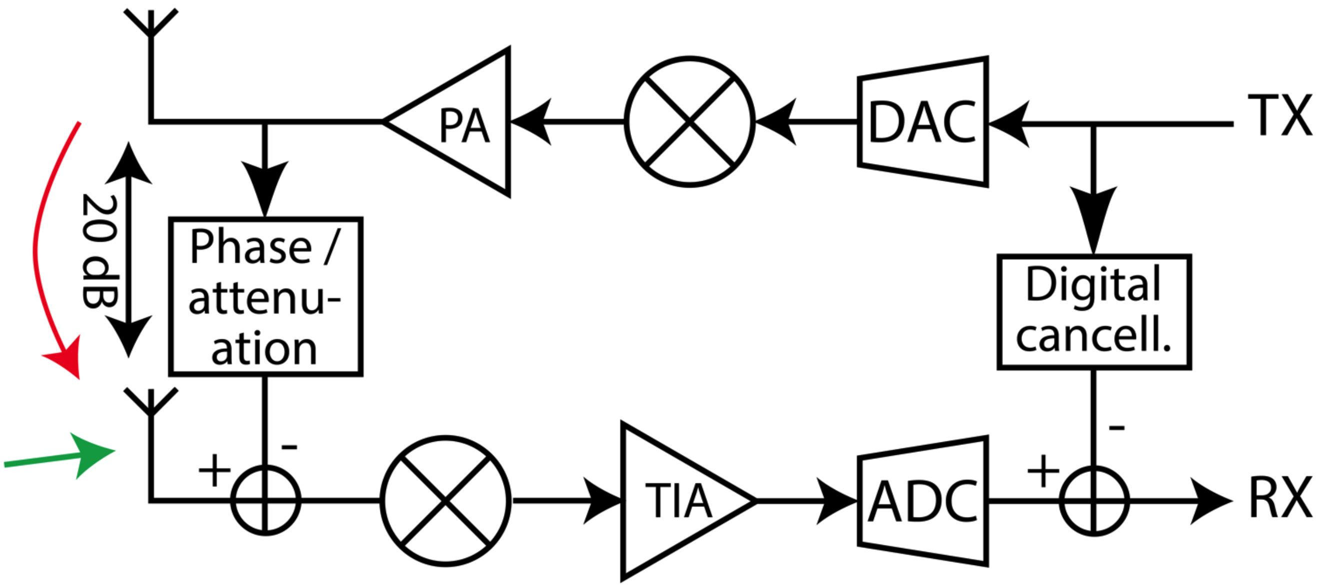
→ 20 to 30 dB to be gained without tackling frequency-selective components!?

Proposal: RF + digital SI-cancellation



Only Gain and Phase correction needed!!

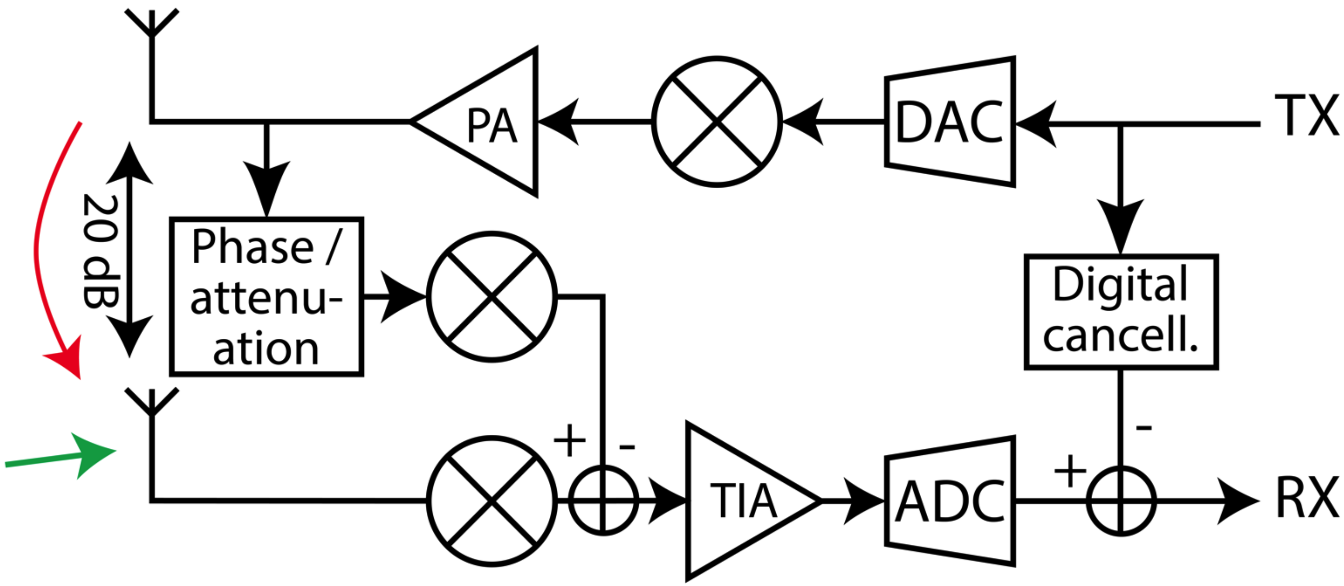
RF + digital SI-cancellation



“Mixer-first”: very good linearity

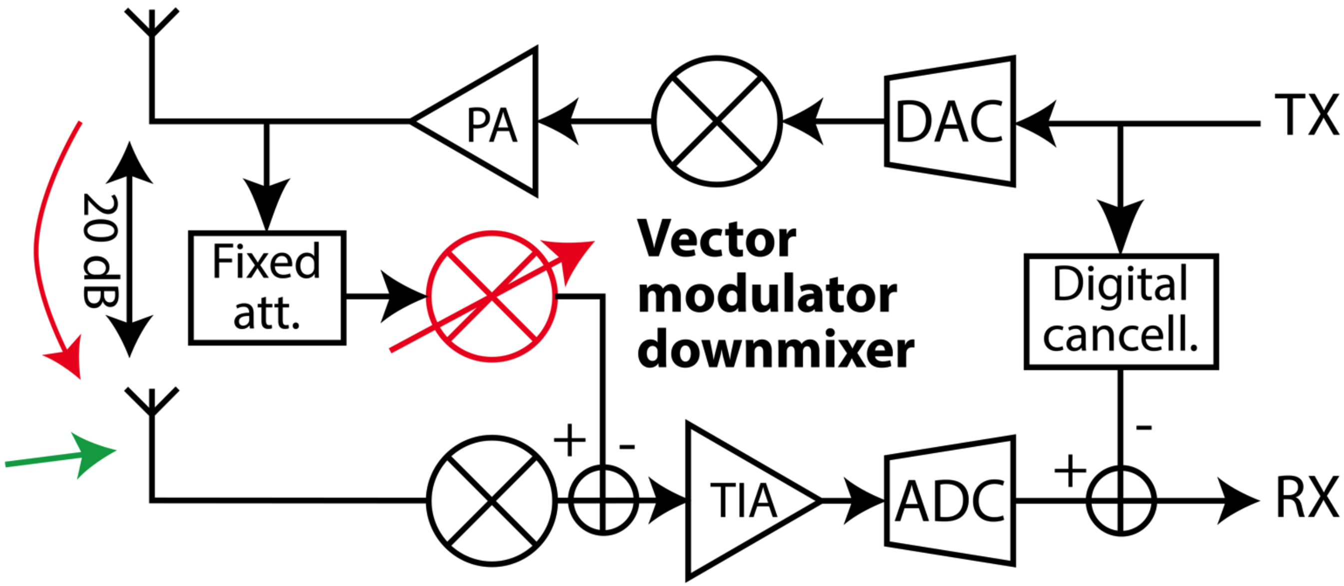
Noise a few dB degraded (but SI is bottleneck!)

Cross-domain cancellation

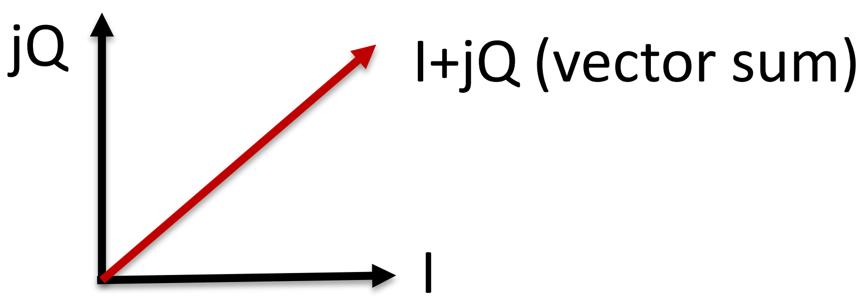


Cancellation TX RF → RX analog BB

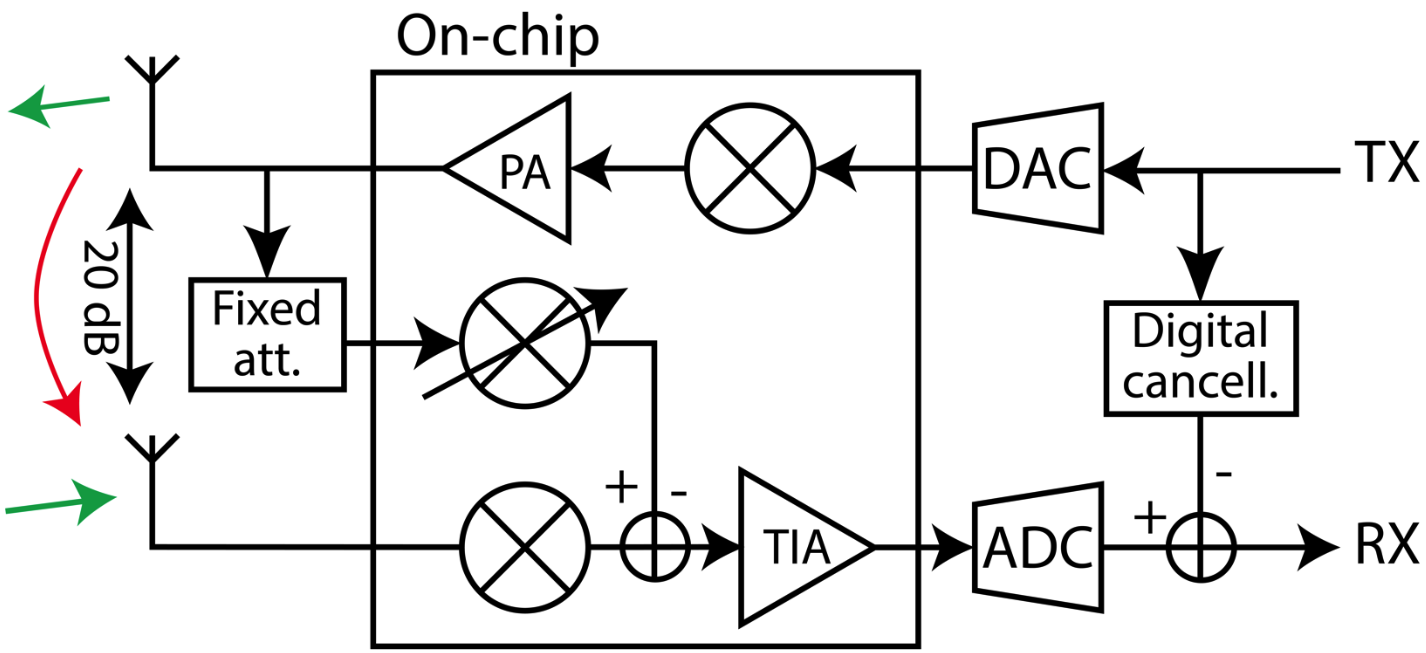
Cross-domain cancellation



Combine phase, attenuation & I/Q downmixing

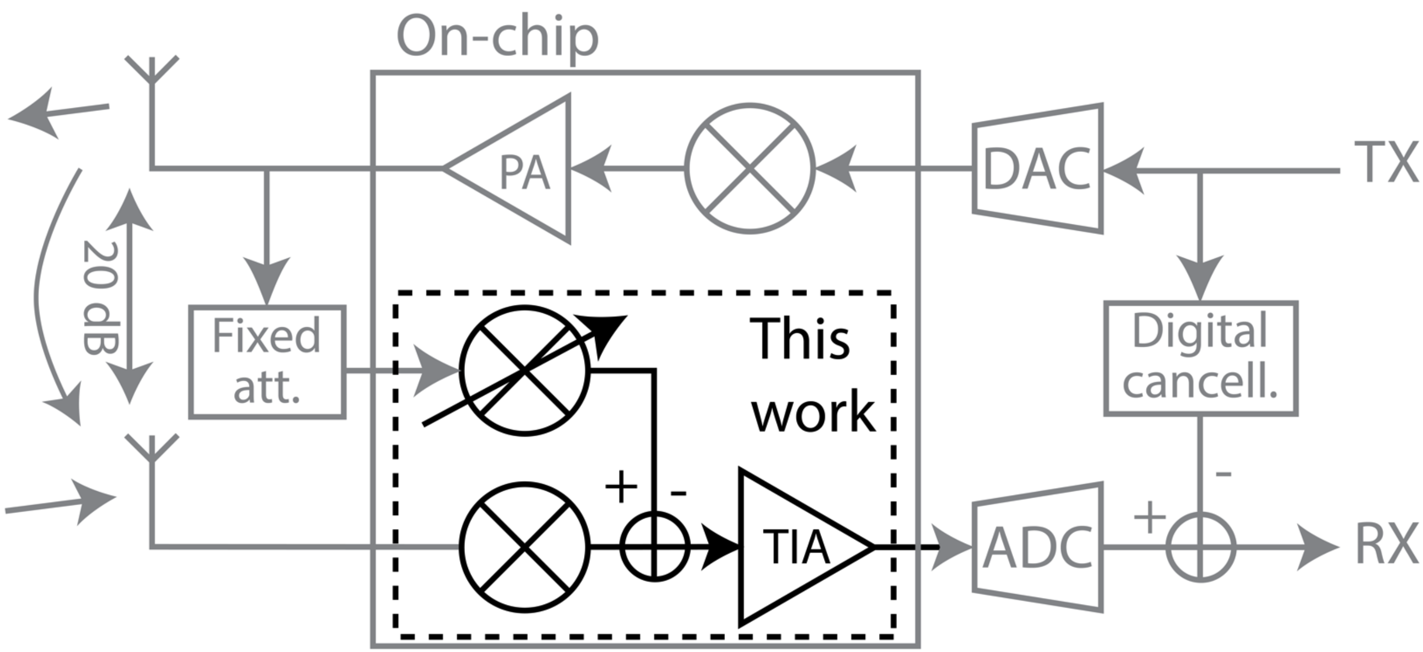


Prototype front-end

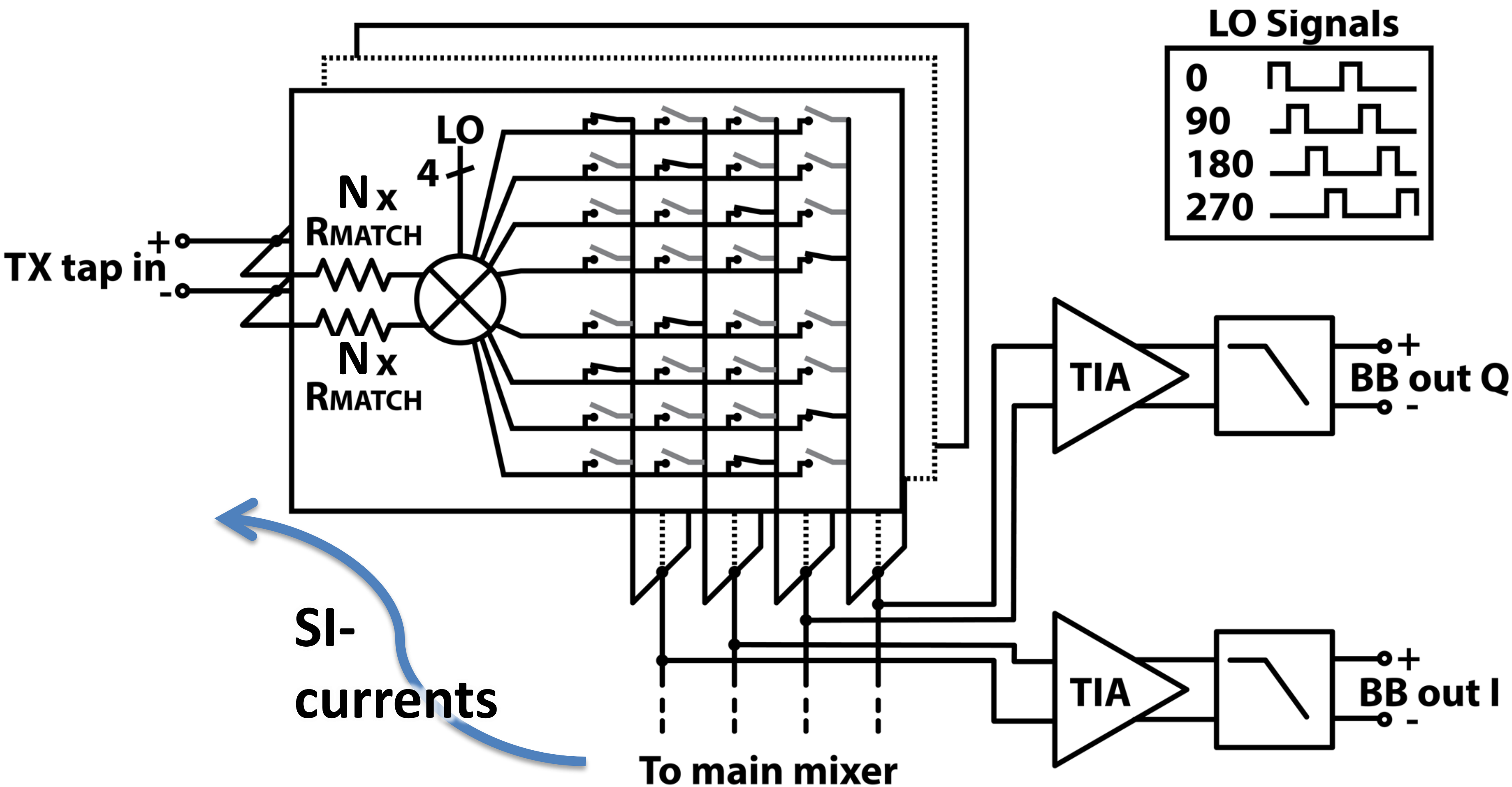


Short-range, low-power full-duplex
High integration potential

Prototype front-end

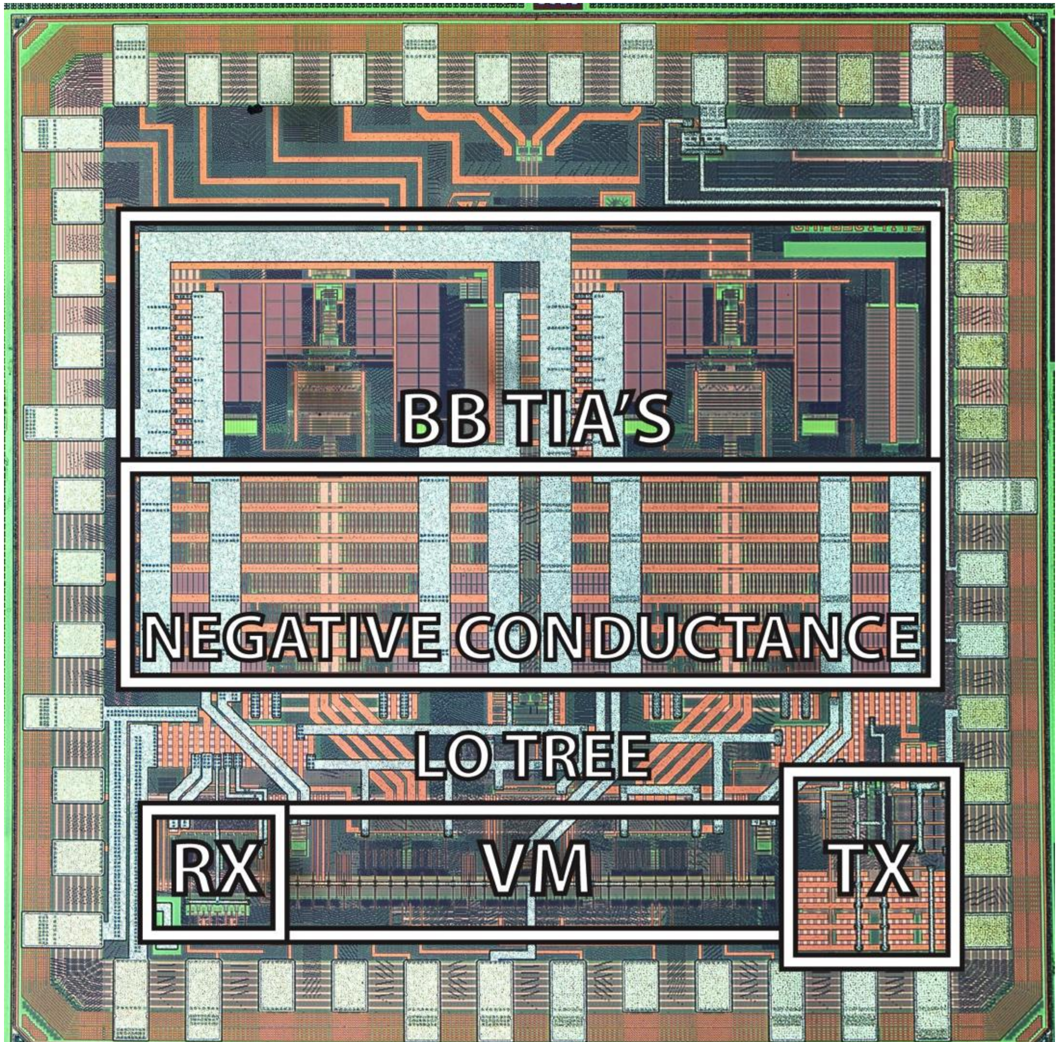


Vector modulator: Switched Resistors



SI diverted through passive networks (extreme linearity)

Chip photograph



65nm CMOS

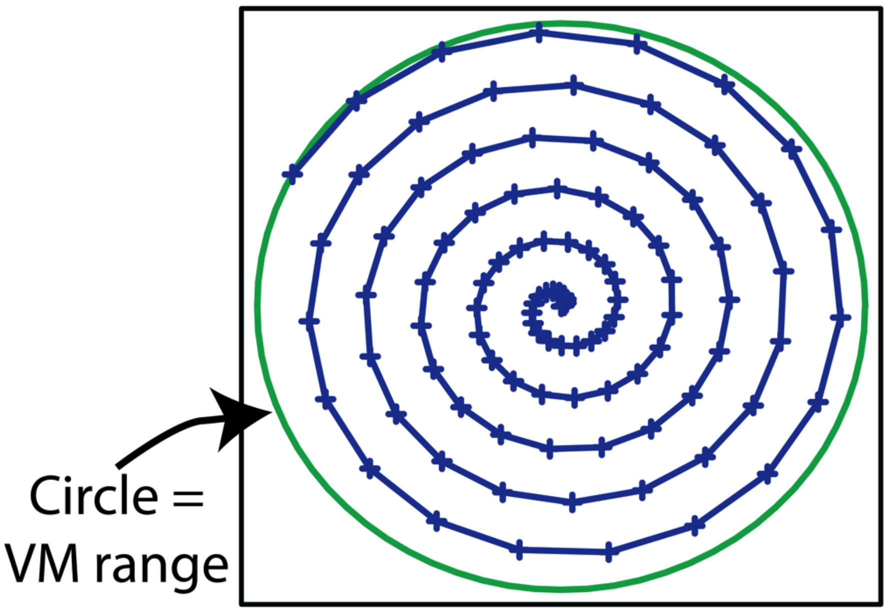
1.2V supply

1.4x1.4mm

Measured: Cancellation

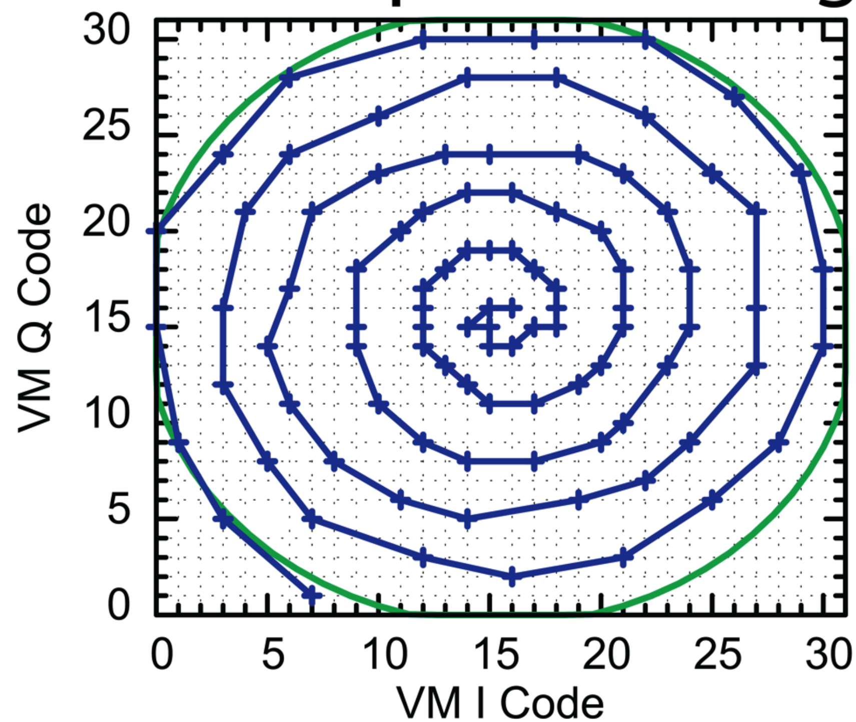
- 20 tones in 16.25 MHz BW @ 2.5 GHz (WiFi-like)
- Emulated SI channel: arbitrary phase & amplitude
- On-chip VM finds best cancellation point
  - Search algorithm: power minimization

Emulated SI-channel

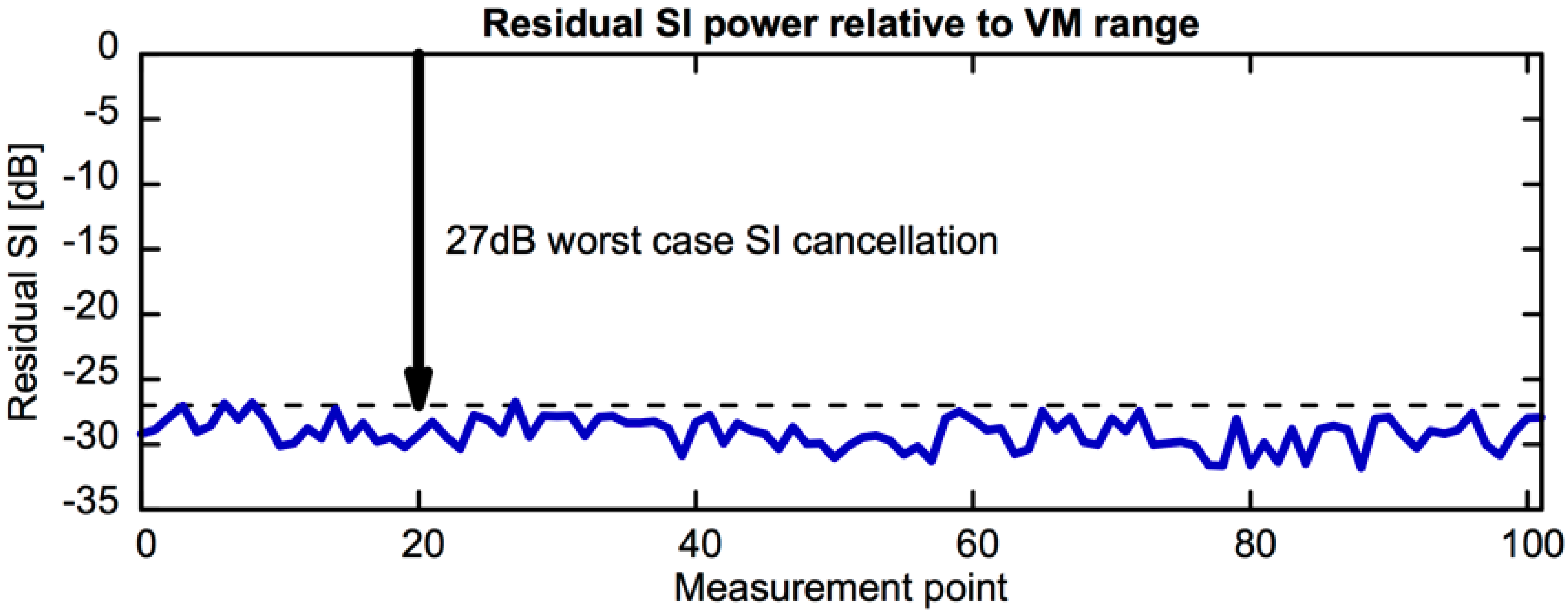


>100 phase/amplitude points

On-chip VM setting



Resulting measured Cancellation



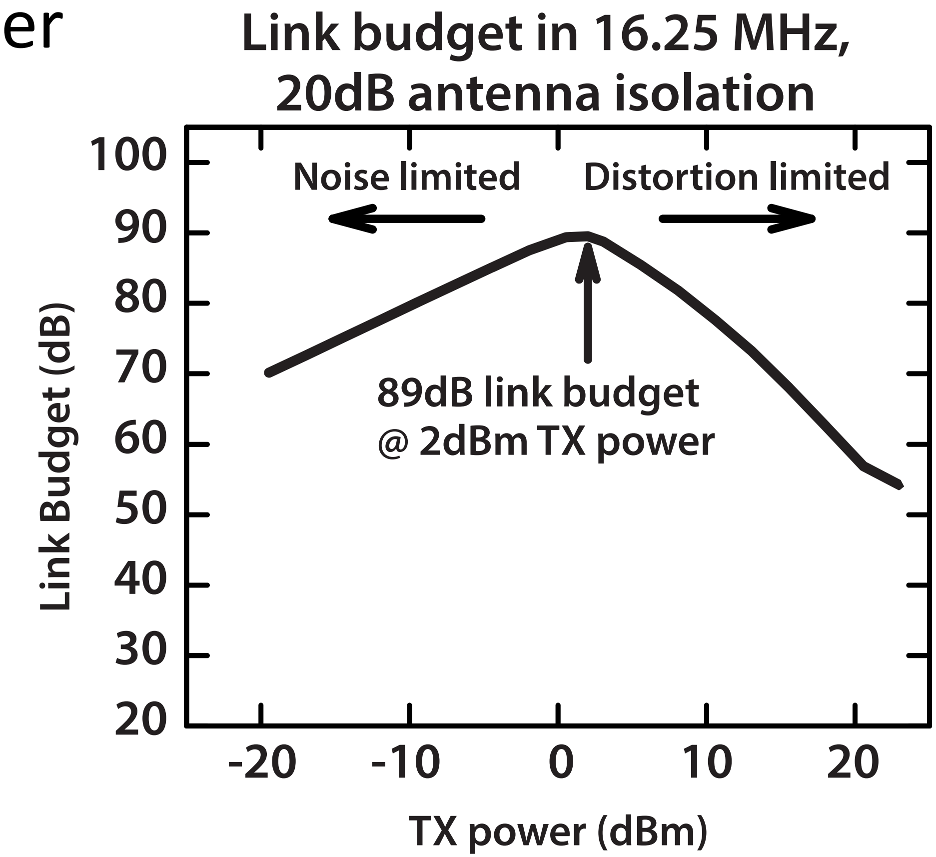
>27dB cancellation for all points

Resulting link budget

- Noise limited: more TX power →Increasing link budget
- Distortion limited region:

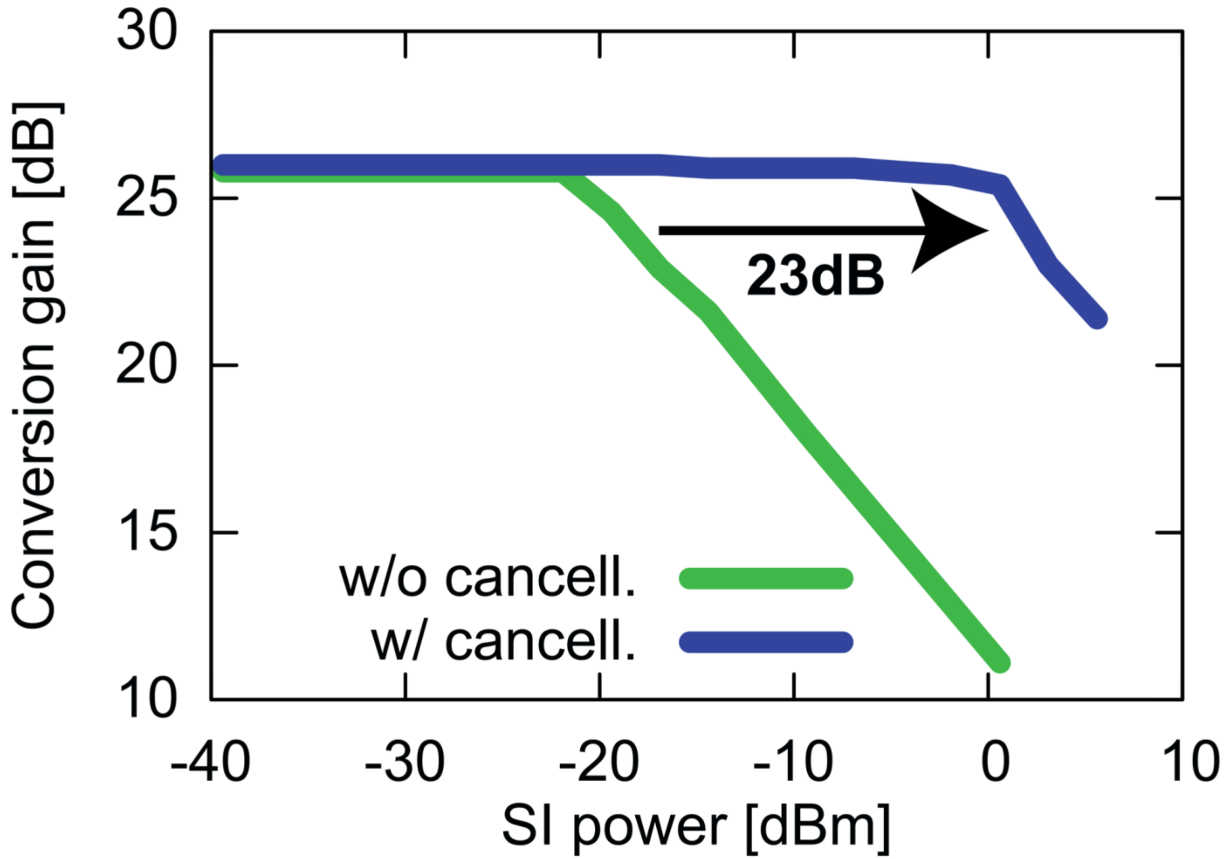
Increasing SI
→RX 3rd order distortion
→Decreasing link budget

- Optimum link budget: **89dB at 2dBm TX power**



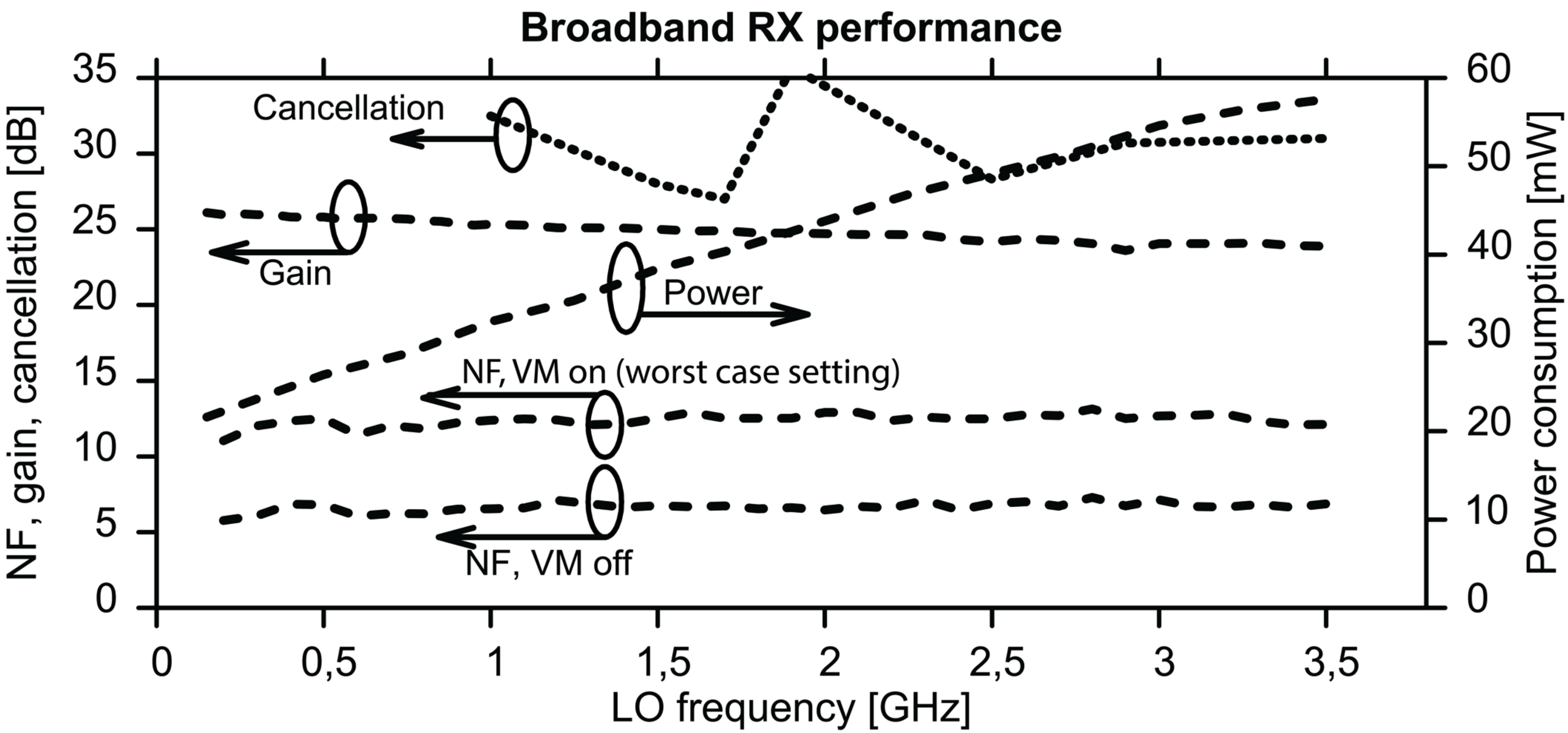
(Assumption: Full 27dB cancellation can be achieved in 16.25MHz BW)

Conversion gain under SI



Desired signal only compressed at >0 dBm SI
= 20dBm TX power at 20dB iso

Broadband RX performance



Frequency-flexible operation & cancellation

Conclusion

Full-duplex hardware:

- requires multi-domain SI-cancellation
- Various promising topologies
- Many challenges still remain in both circuit design and higher layers

References

Overview papers:

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Dual polarized antenna:

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- van den Broek, D.-J.; Klumperink, E.A.M.; Nauta, B., "19.2 A self-interference-cancelling receiver for in-band full-duplex wireless with low distortion under cancellation of strong TX leakage," Solid- State Circuits Conference - (ISSCC), 2015 IEEE International , vol., no., pp.1,3, 22-26 Feb. 2015
- D.-J.van den Broek, E. Klumperink , and B. Nauta, "A self-interference cancelling front-end for in-band full-duplex wireless and its phase noise performance," in Radio Frequency Integrated Circuits Symposium, 2015 IEEE, 2015