A Dual-Frequency 0.7-to-1GHz Balance Network for Electrical Balance Duplexers

Benjamin Hershberg[1], Barend van Liempd[1,2], Xiaoqiang Zhang[1], Piet Wambacq[1,2], Jan Craninckx[1]

[1]imec, Heverlee, Belgium
[2]Vrije Universiteit Brussel, Brussels, Belgium

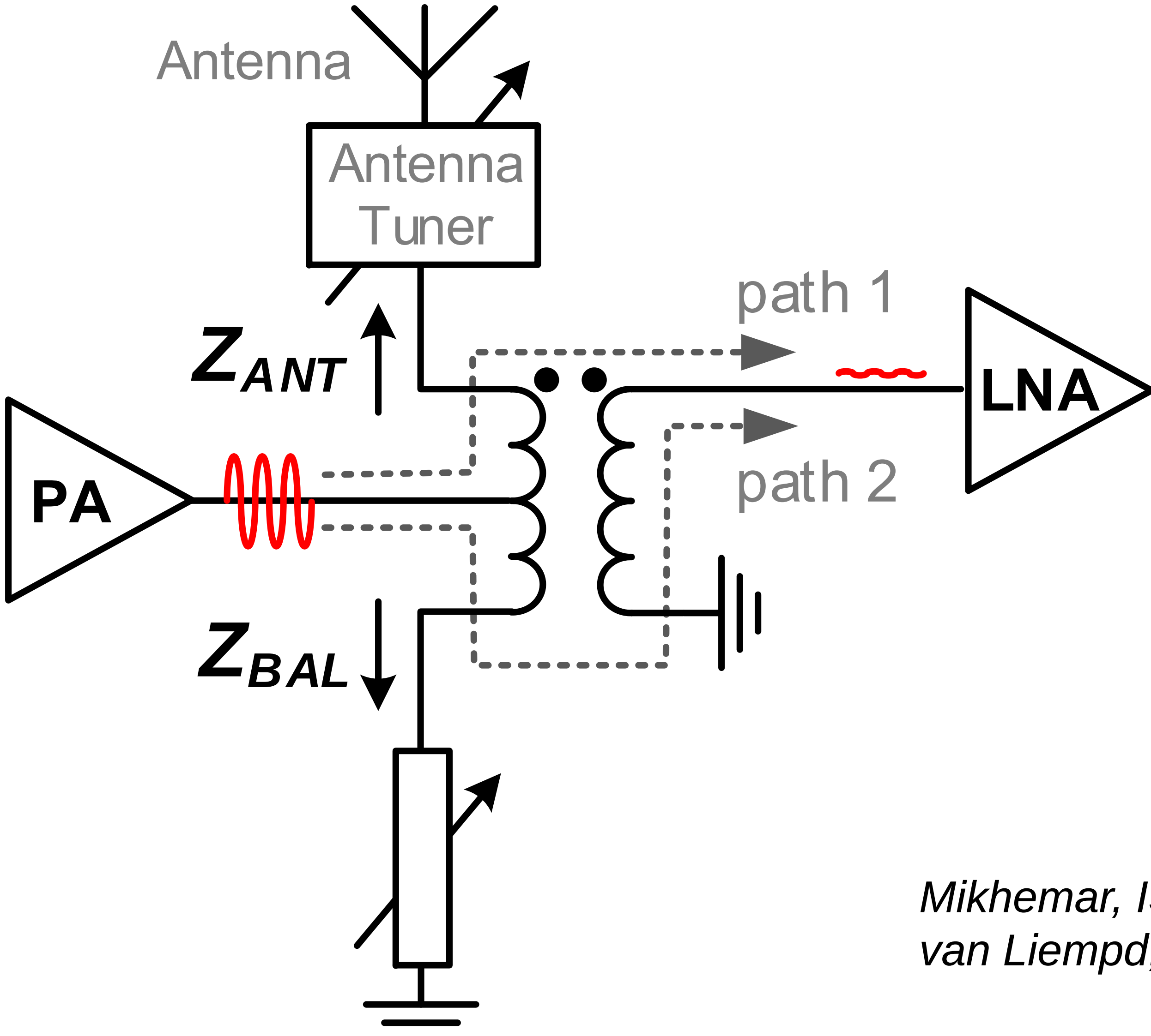
Motivation

Mobile RF frontends use SAW filters and RF switches to support FDD

- iphone 6s
  - 19 FDD-LTE bands
  - 0.7 – 2.4 GHz

- Cost
- Area
- Performance

Background: Electrical Balance Duplexer

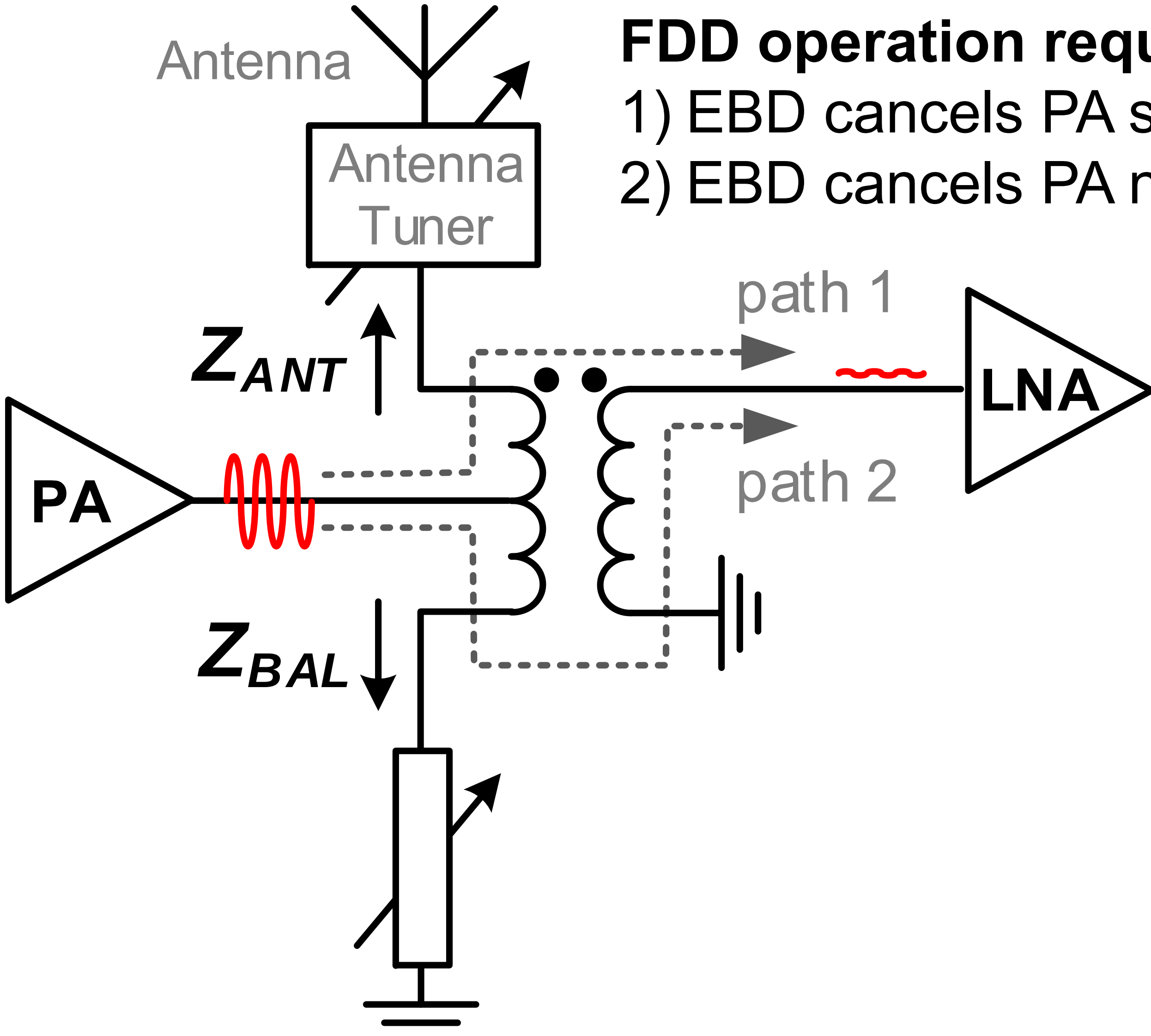


Mikhemar, ISSCC 2009
van Liempd, ISSCC 2015

Background: Electrical Balance Duplexer

FDD operation requires that:

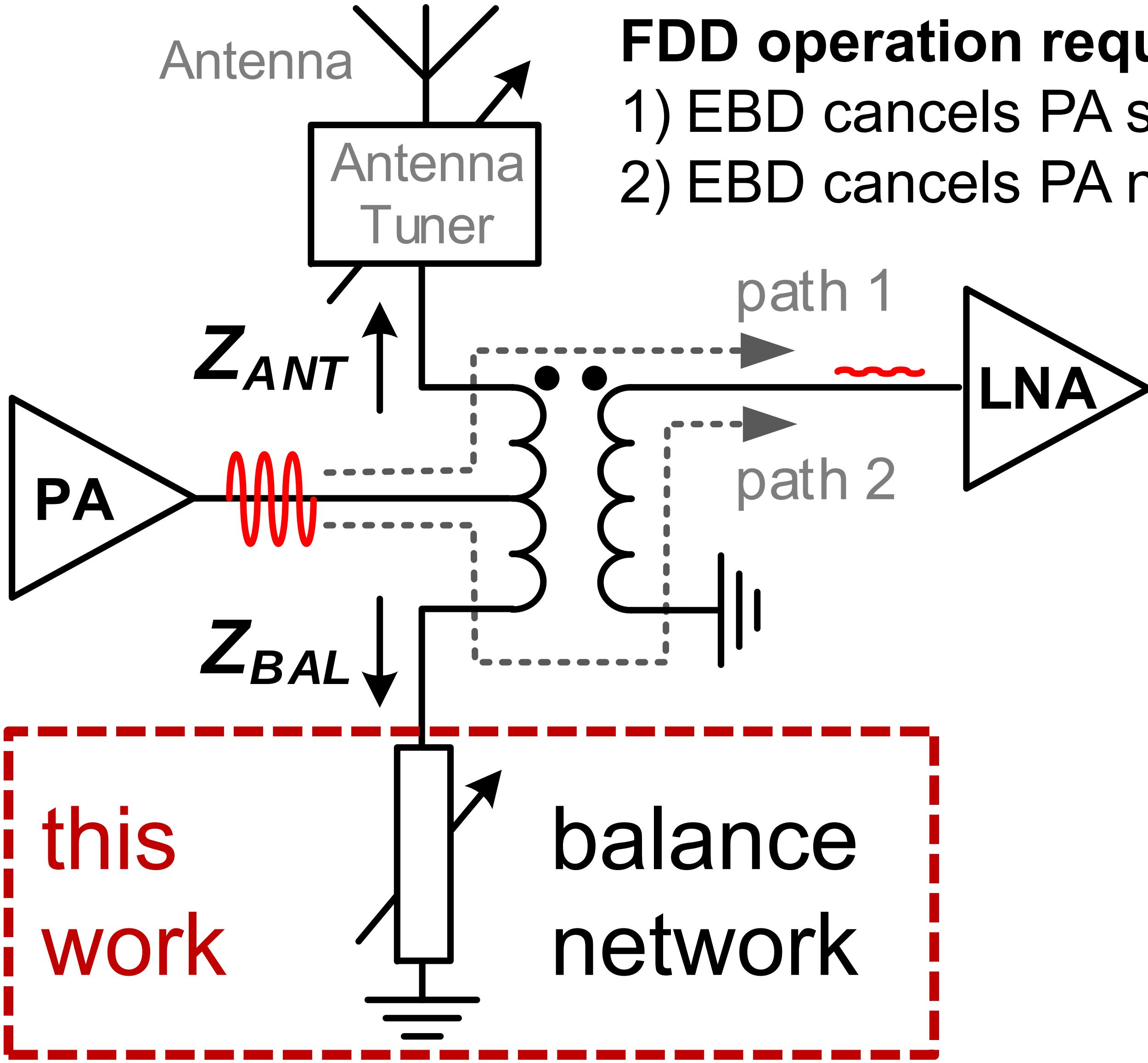
1) EBD cancels PA signal at f_{TX}
2) EBD cancels PA noise at f_{RX}



Background: Electrical Balance Duplexer

FDD operation requires that:

1) EBD cancels PA signal at f_{TX}
2) EBD cancels PA noise at f_{RX}



Key Challenge

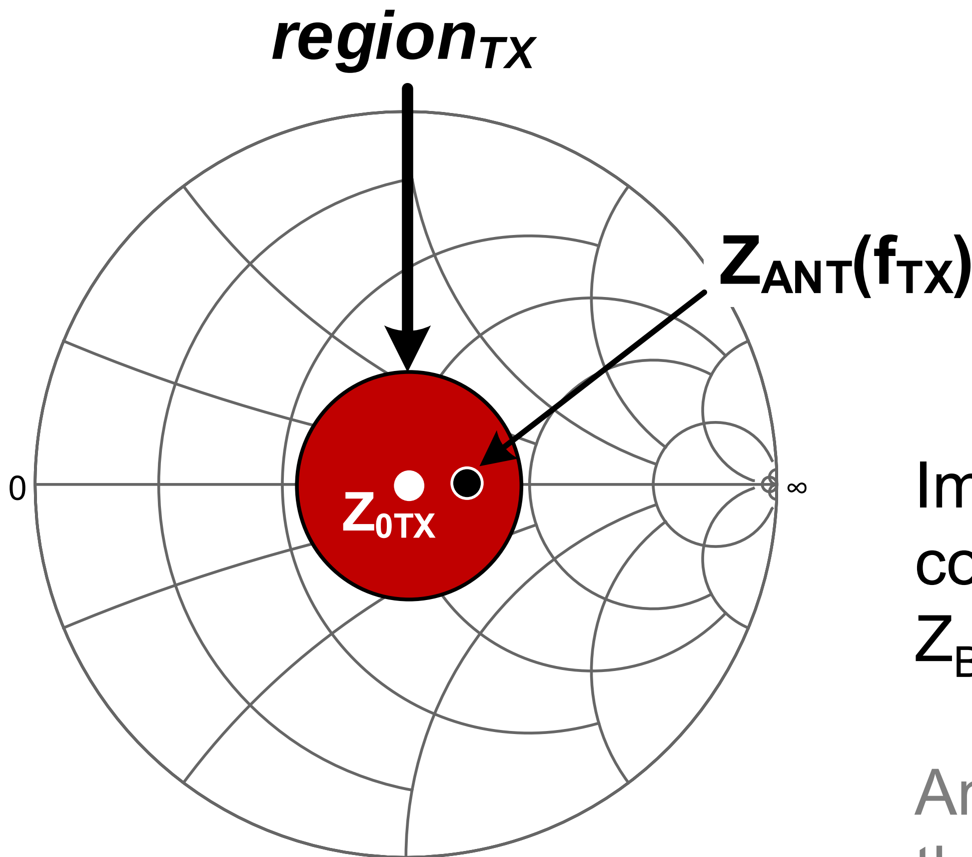
The antenna impedance is

Frequency dependent

Time dependent

Z_{BAL} must track these variations at both f_{TX} *and* f_{RX}

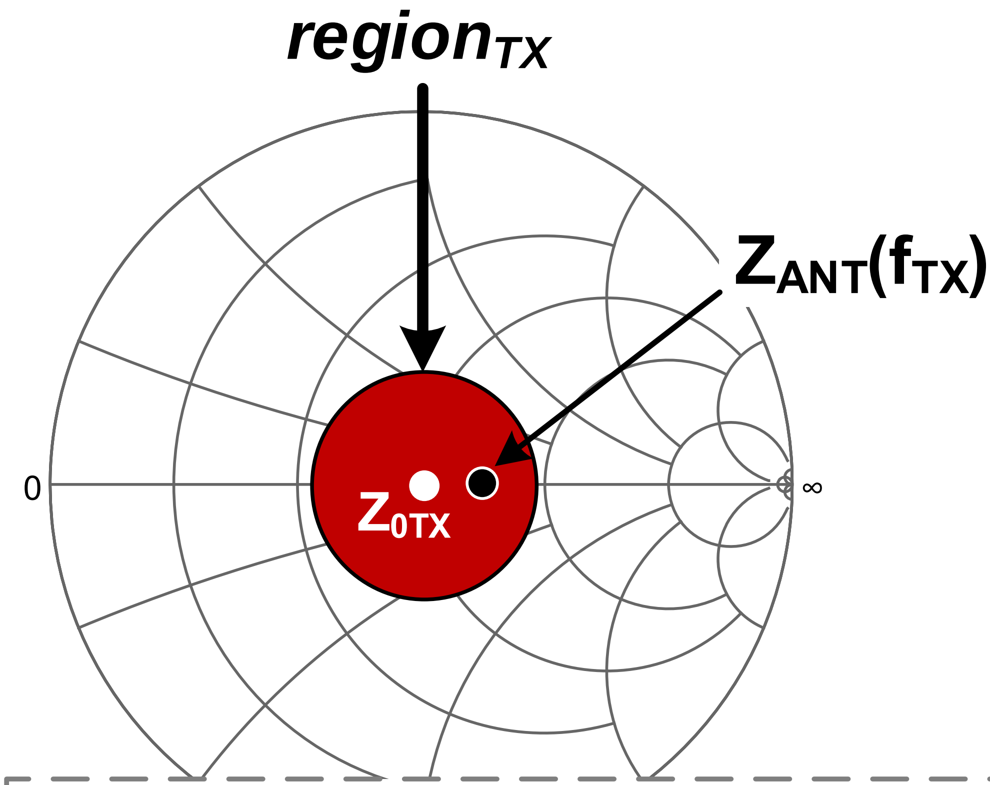
Tuning Spec: $region_{TX}$



Impedance-variation coverage region of Z_{BAL} at f_{TX}

Antenna tuner can reduce the required size

Tuning Spec: region$_{TX}$

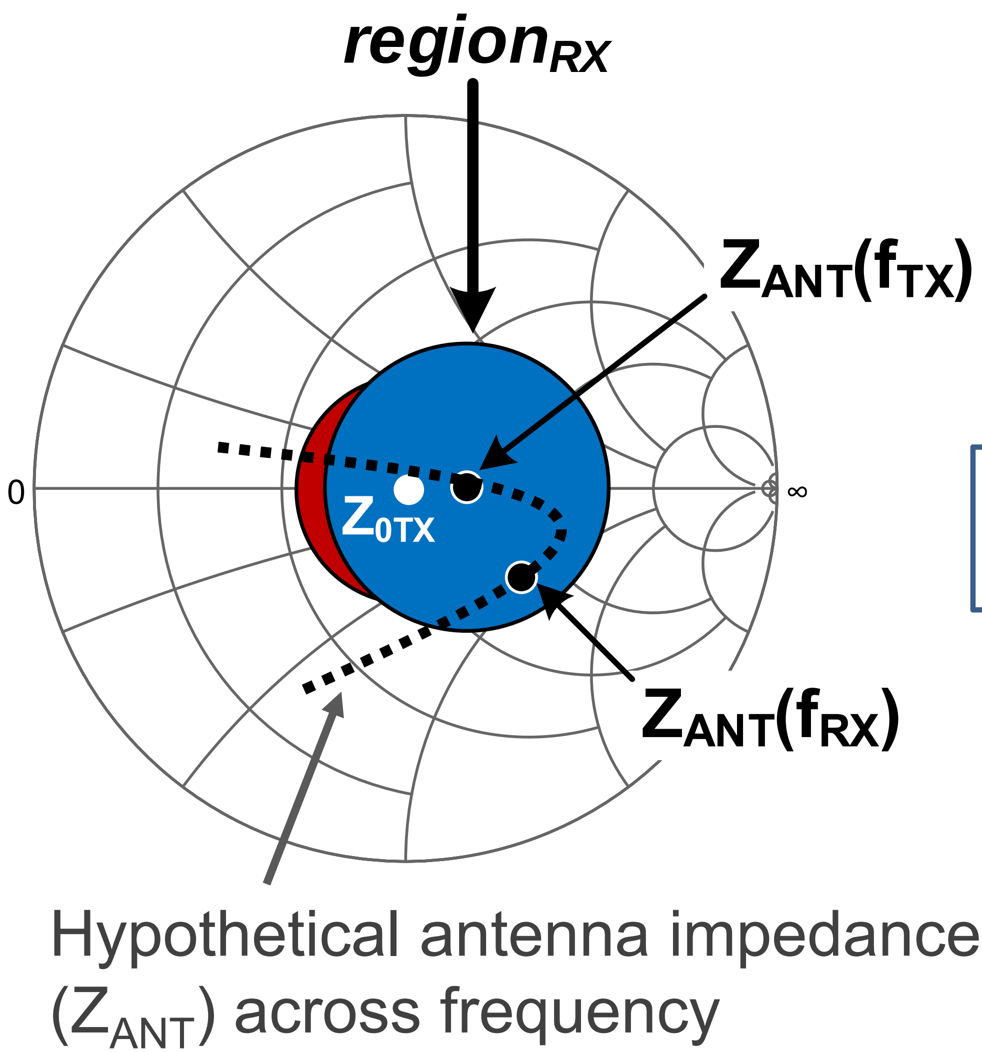


Described by a pair of values:

1) the center impedance Z_{0TX} (Ω)

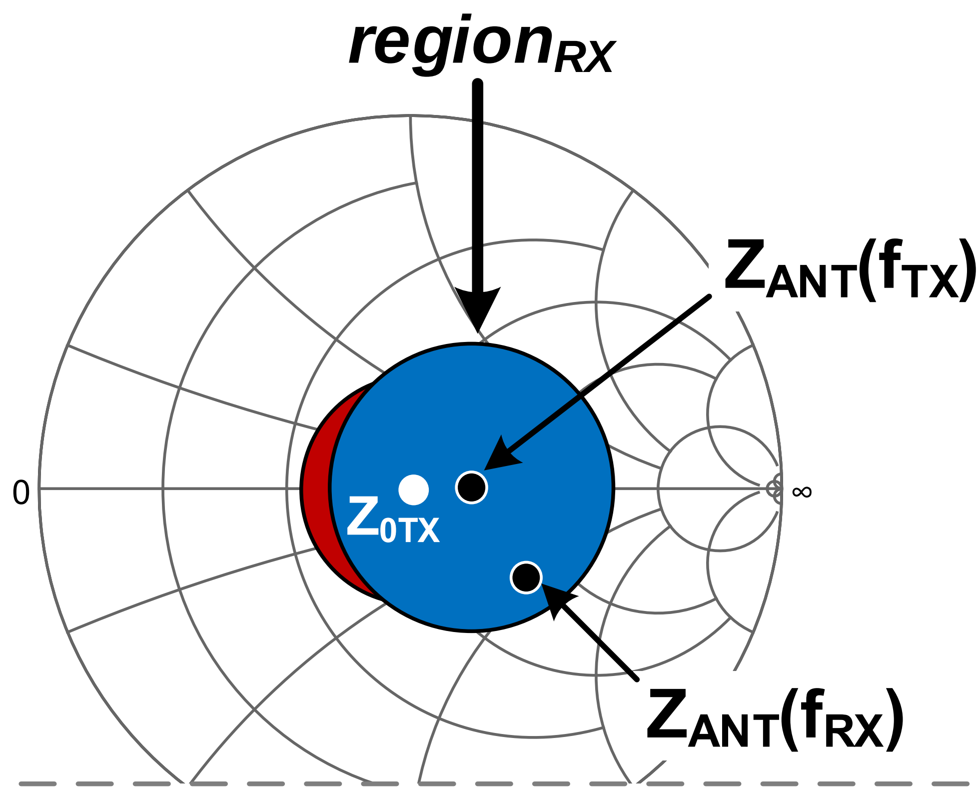
2) the perimeter of region$_{TX}$ (VSWR)

Tuning Spec: $region_{RX}$



Drift ∝ Q ∝ BW^{-1}

Tuning Spec: region_{RX}



Described by:

1) max rate of impedance change allowed for Z_{ANT} (% / MHz w.r.t. f_{ref})

Tuning Specs: region$_{TX}$ & region$_{RX}$

The balance network can synthesize **all** impedances in region$_{TX}$ at f_{TX}…

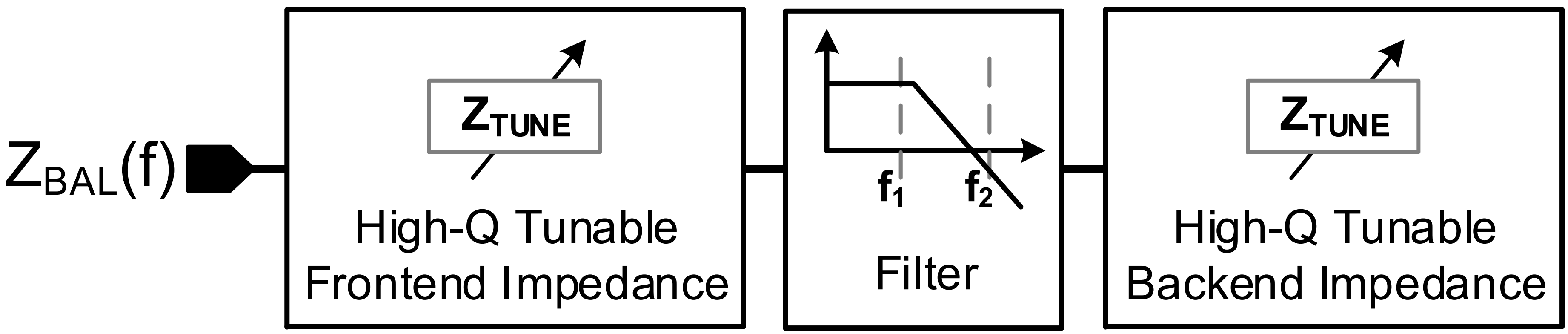
…and *simultaneously* generate **any** impedance in region$_{RX}$ at f_{RX}.

Dual-Frequency Tuning Concept

High-level perspective

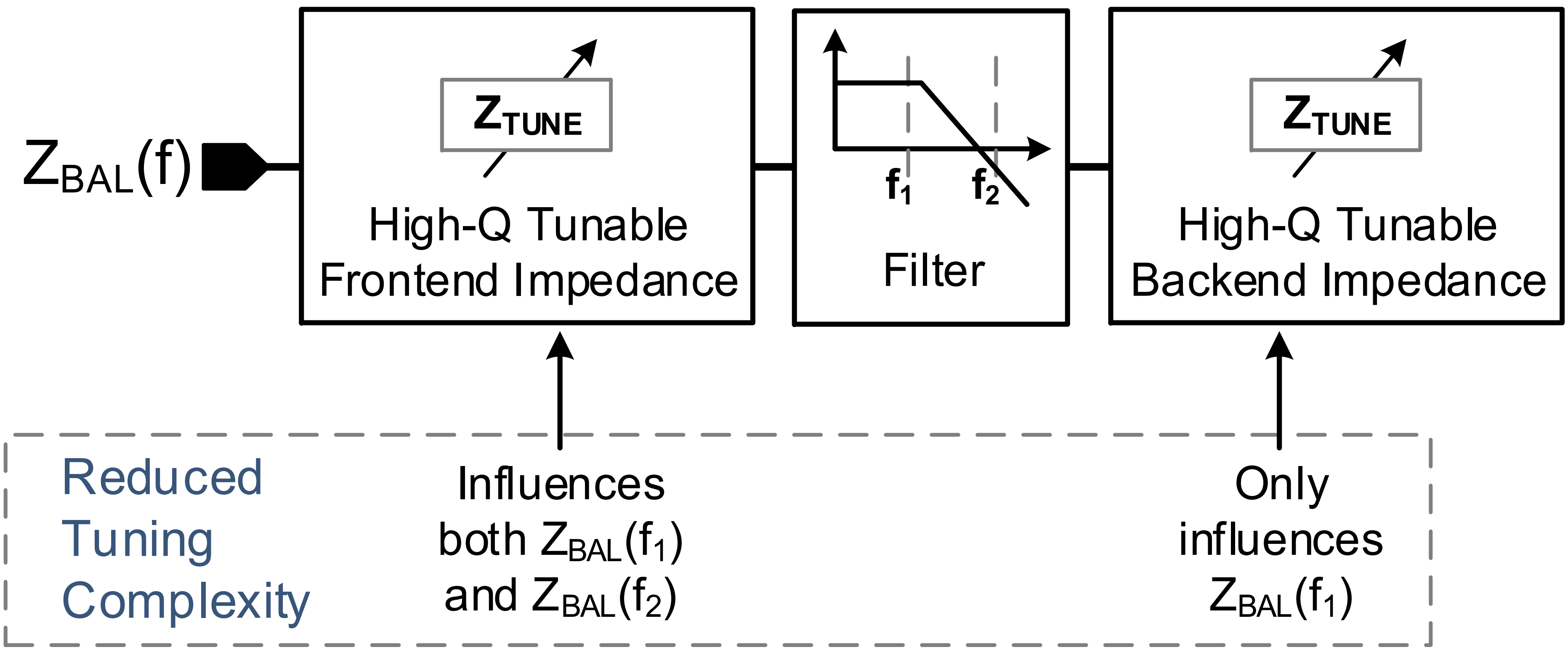
Dual-frequency tuning concept

Core idea: Make certain tuning knobs only influence Z_{BAL} at f_1 and not at f_2



Dual-frequency tuning concept

Core idea: Make certain tuning knobs only influence Z_{BAL} at f_1 and not at f_2

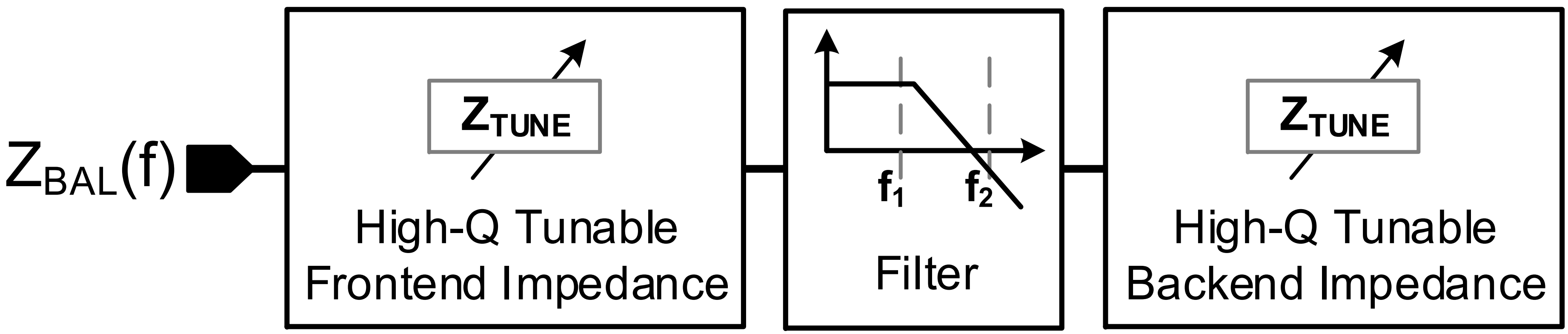


Dual-frequency tuning concept

Full Region$_{RX}$ Coverage

For each $Z_{BAL}(f_2)$ set here…

…a wide range of $Z_{BAL}(f_1)$'s can be set here



Reduced Tuning Complexity

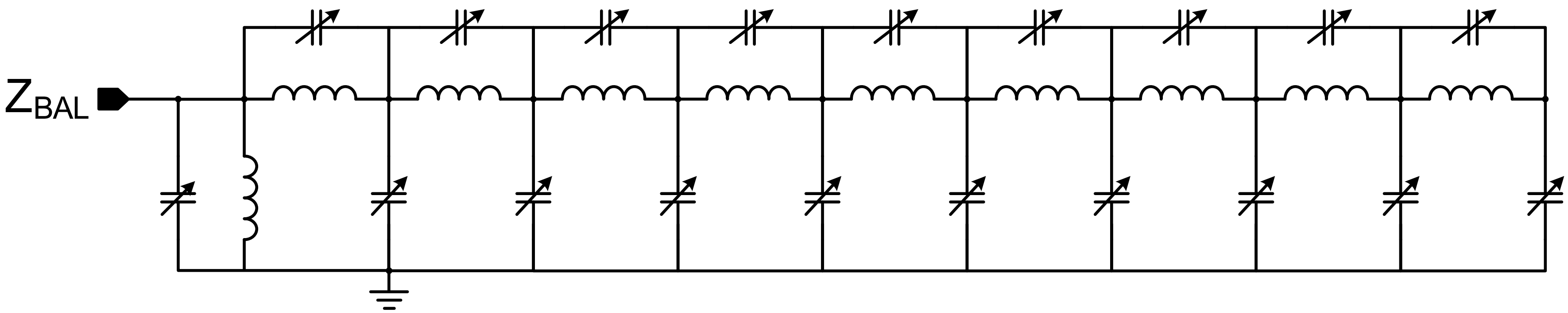
Influences both $Z_{BAL}(f_1)$ and $Z_{BAL}(f_2)$

Only influences $Z_{BAL}(f_1)$

Circuit Implementation

Practical application of theory

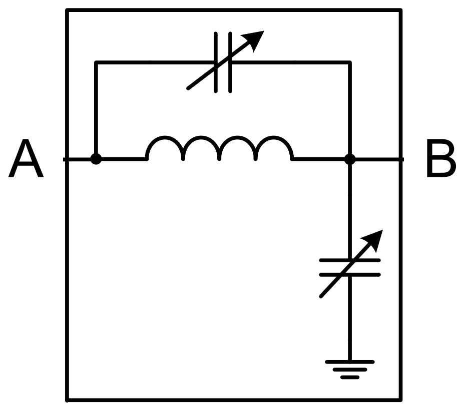
Circuit Implementation



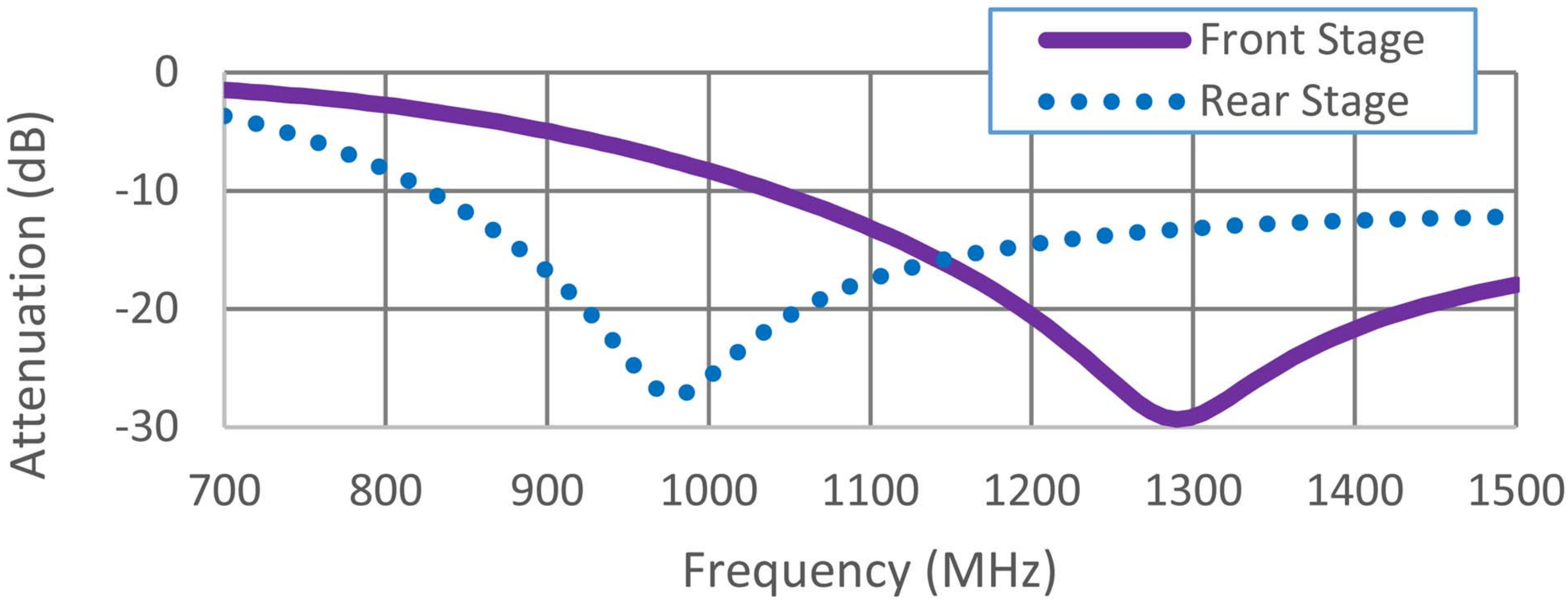
- Distributed implementation of conceptual blocks
  - Efficient, flexible approach
- Uses only high-Q reactive elements
  - Maximizes frequency dependency
  - Must still synthesize impedances in vicinity of 50Ω

Guaranteed low-pass filtering

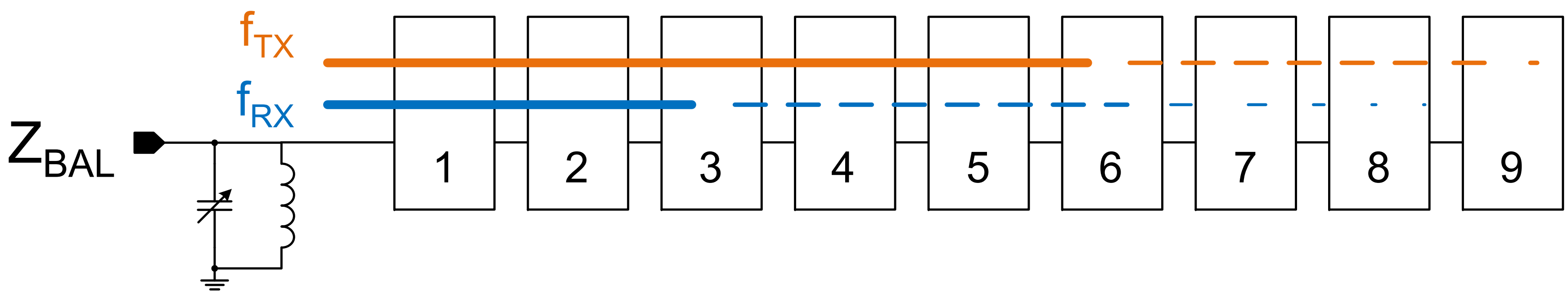
stage circuit

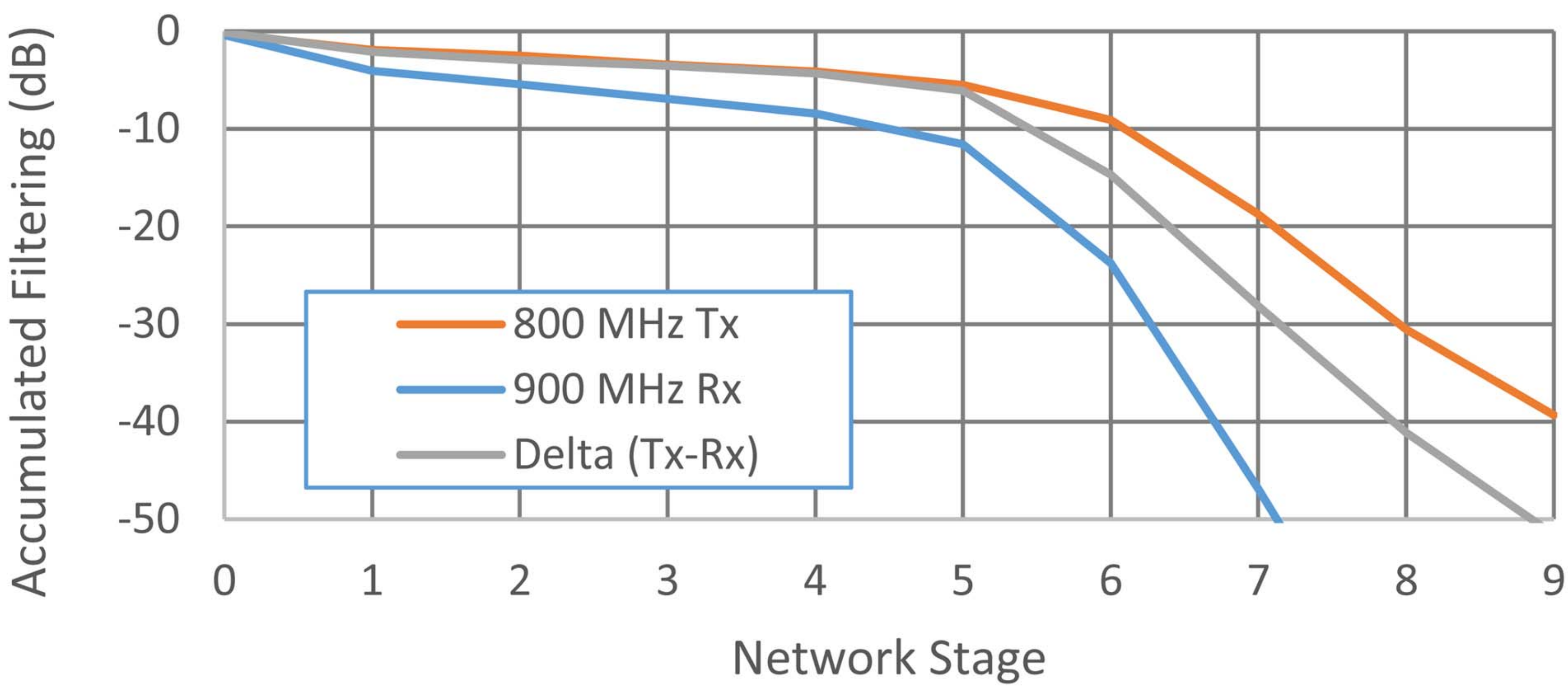


- Stages 1-5 resonance always > 1GHz.
  - Guarantees low-pass characteristic in-band
- Stages 6-9 resonance can be < 1GHz
  - Needed to fully cover all parts of region$_{RX}$



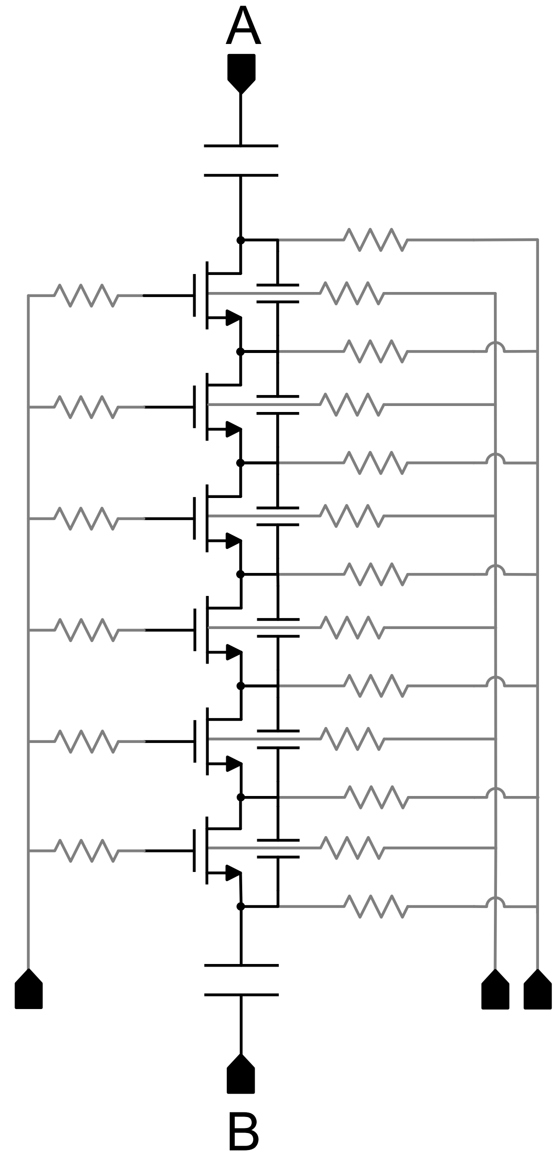
Accumulated filtering across stages



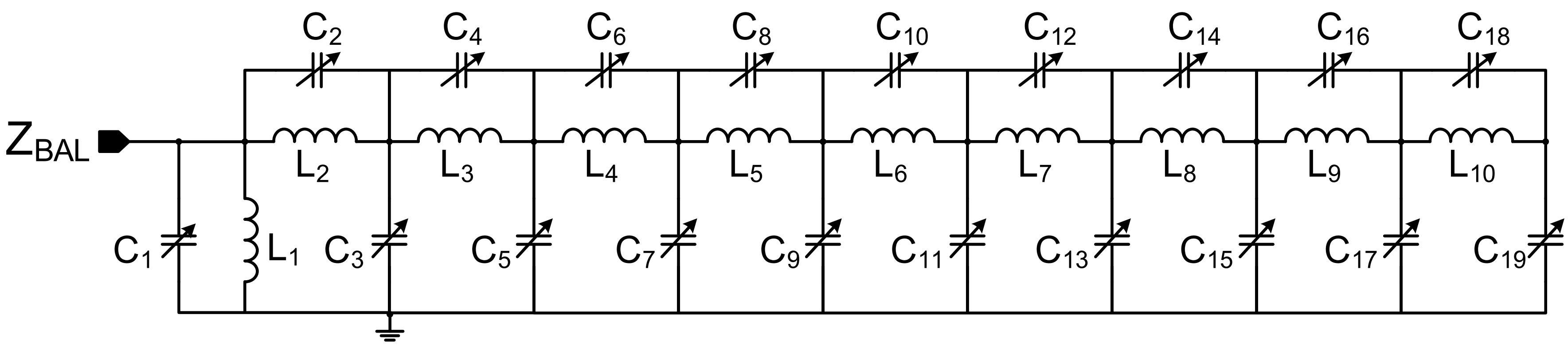


Tunable capacitors

- Digitally controlled banks
- 6 stacked SOI switches for power handling
- Additional drain-source capacitors for improved off-state voltage equalization



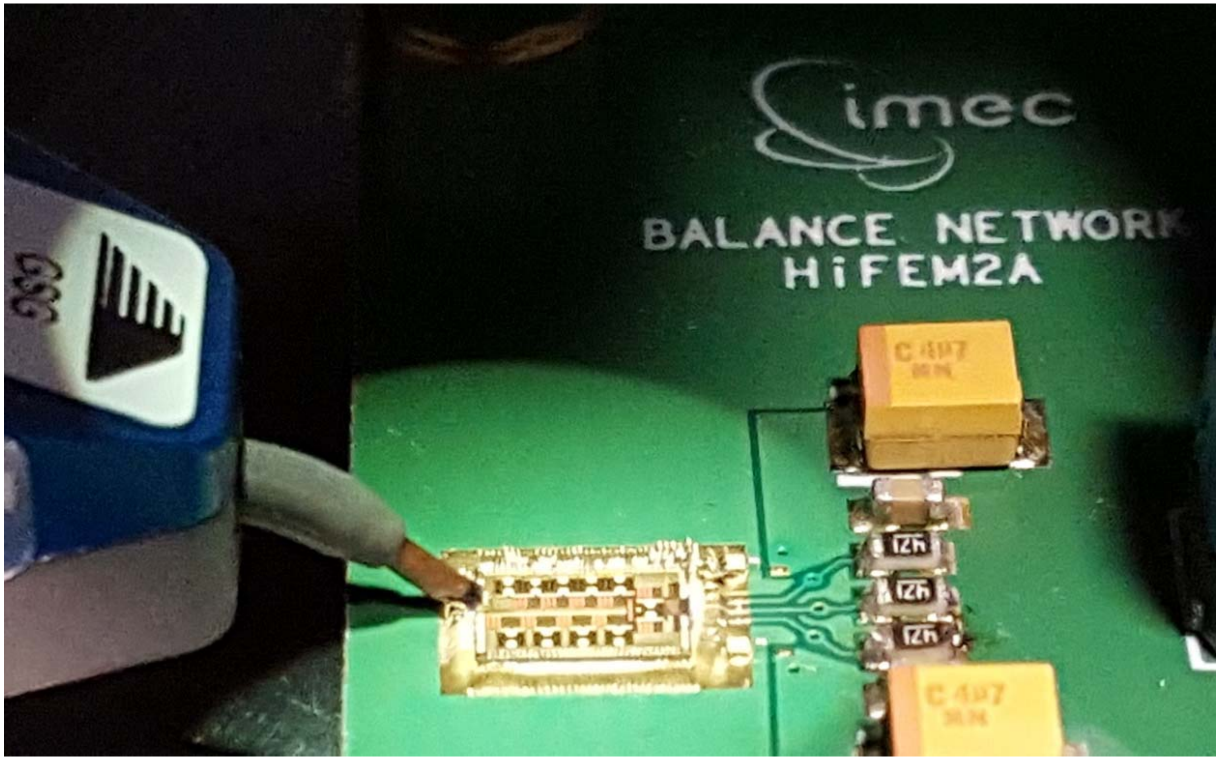
Custom Simulation Engine



- What are the optimal component values?
- How do we validate for $region_{TX}$, $region_{RX}$?

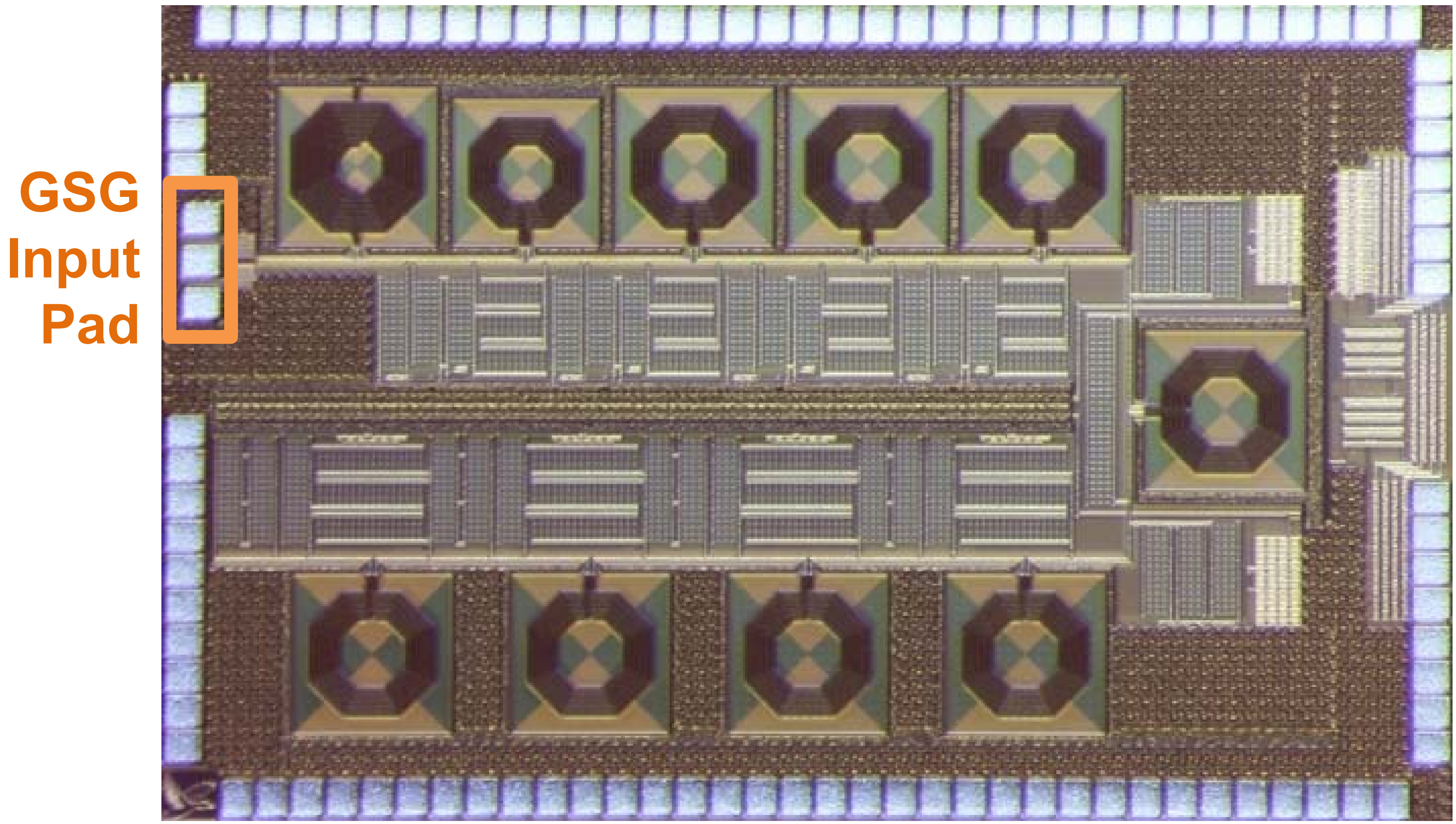
Custom Simulation Engine

- Brute-force design and validation
- Typical design iteration
  – 50 million balance network settings
  – < 2 minutes
- Final validation
  – 100 billion balance network settings
  – approx. 2 days



Measurement Results

Chip Photo

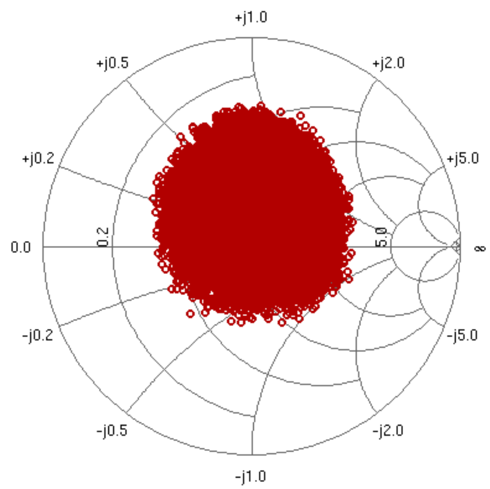


8.28 mm^2 (3.6 mm x 2.3 mm)

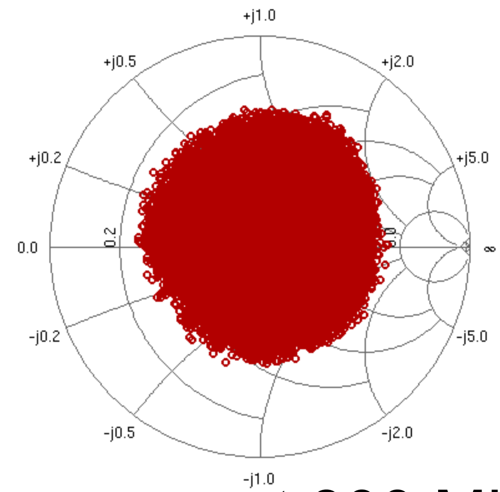
Measured Tuning Capability

Technology	0.18µm RF SOI CMOS
Chip Area	$8.28mm^2$ (3.6mm x 2.3mm)
Operating Range	0.7 GHz – 1.0 GHz
$Region_{TX}$	1.1:1 VSWR, 54+j5Ω
$Region_{RX}$	1.2%/MHz (w.r.t. 800MHz)
LTE Bands Validated	5, 6, 8, 12, 13, 14, 17, 18, 19, 20

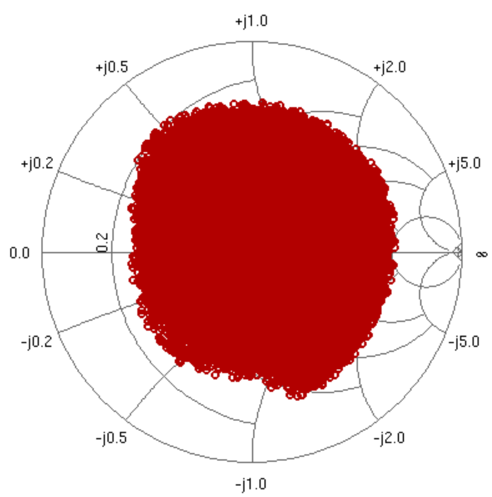
Single Frequency Tuning Range



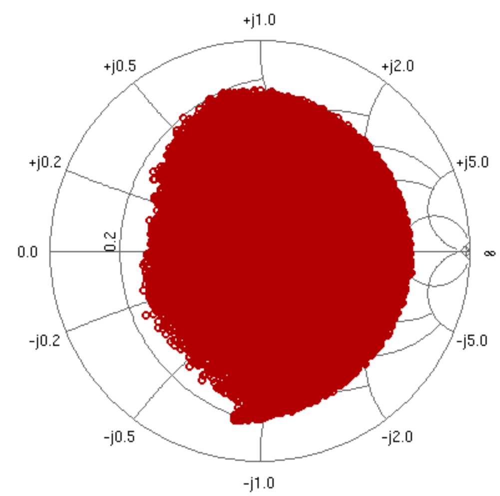
Z_{BAL} range at 700 MHz



Z_{BAL} range at 800 MHz

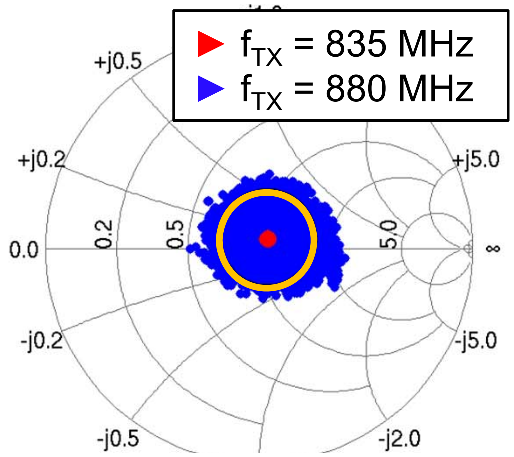


Z_{BAL} range at 900 MHz

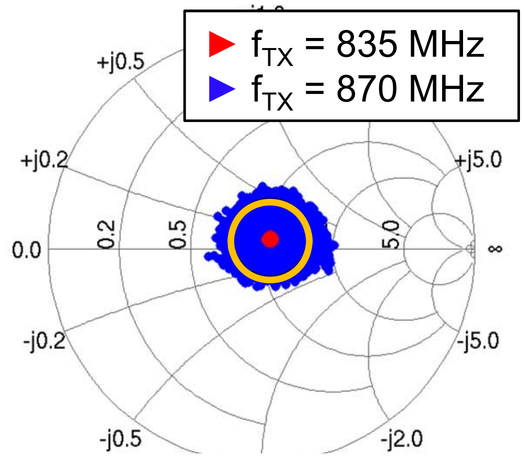


Z_{BAL} range at 1 GHz

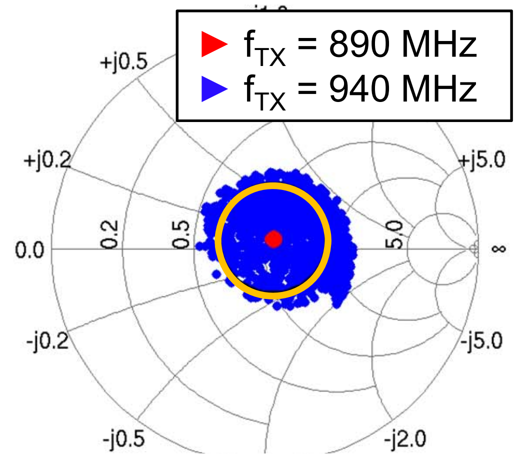
region$_{RX}$ for $Z_{BAL}(f_{TX}) = Z_{0TX}$



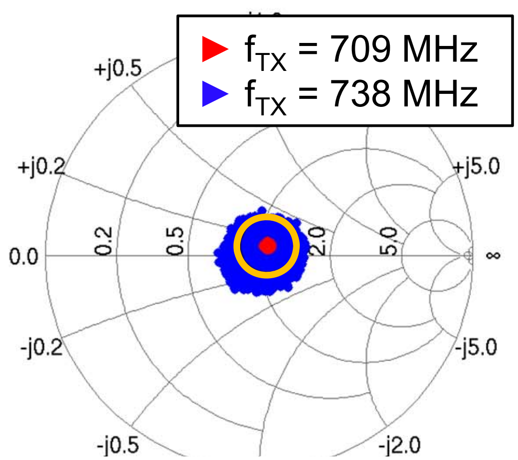
Band 5



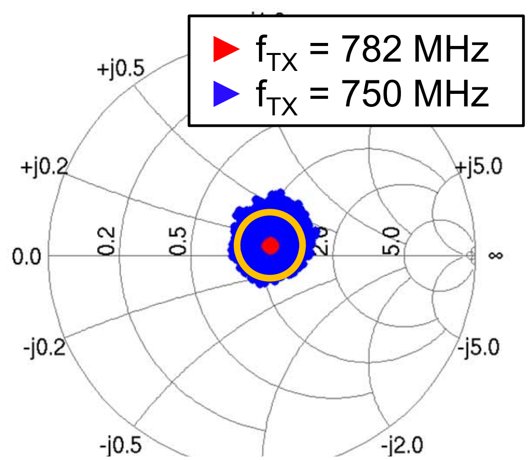
Band 6



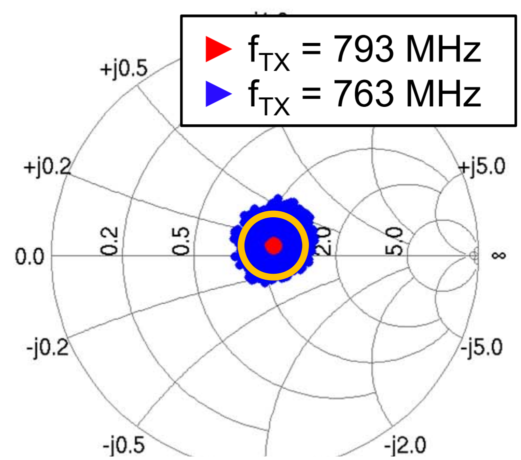
Band 8



Band 12

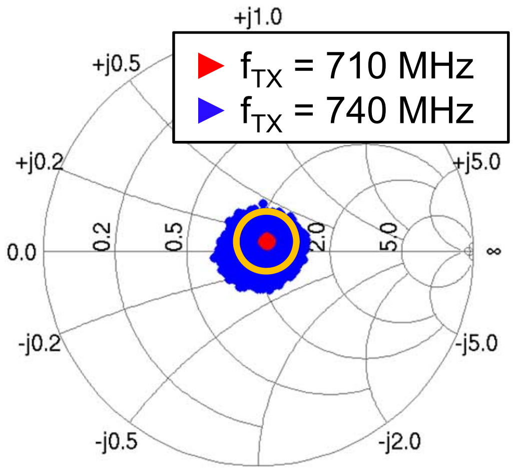


Band 13

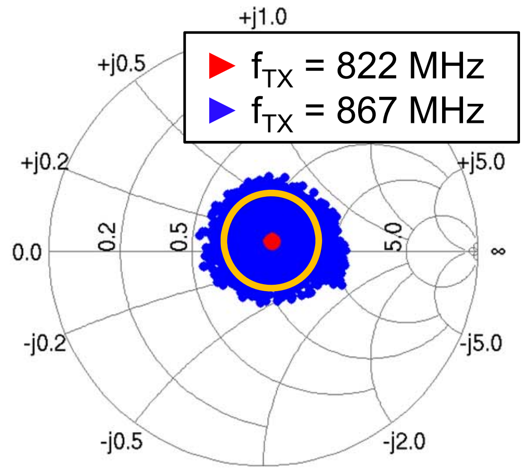


Band 14

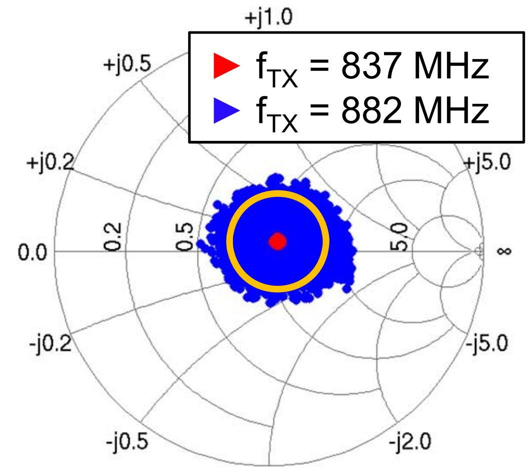
region$_{RX}$ for $Z_{BAL}(f_{TX}) = Z_{0TX}$



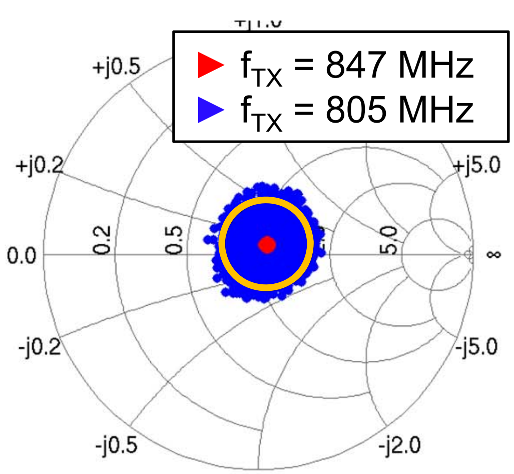
Band 17



Band 18

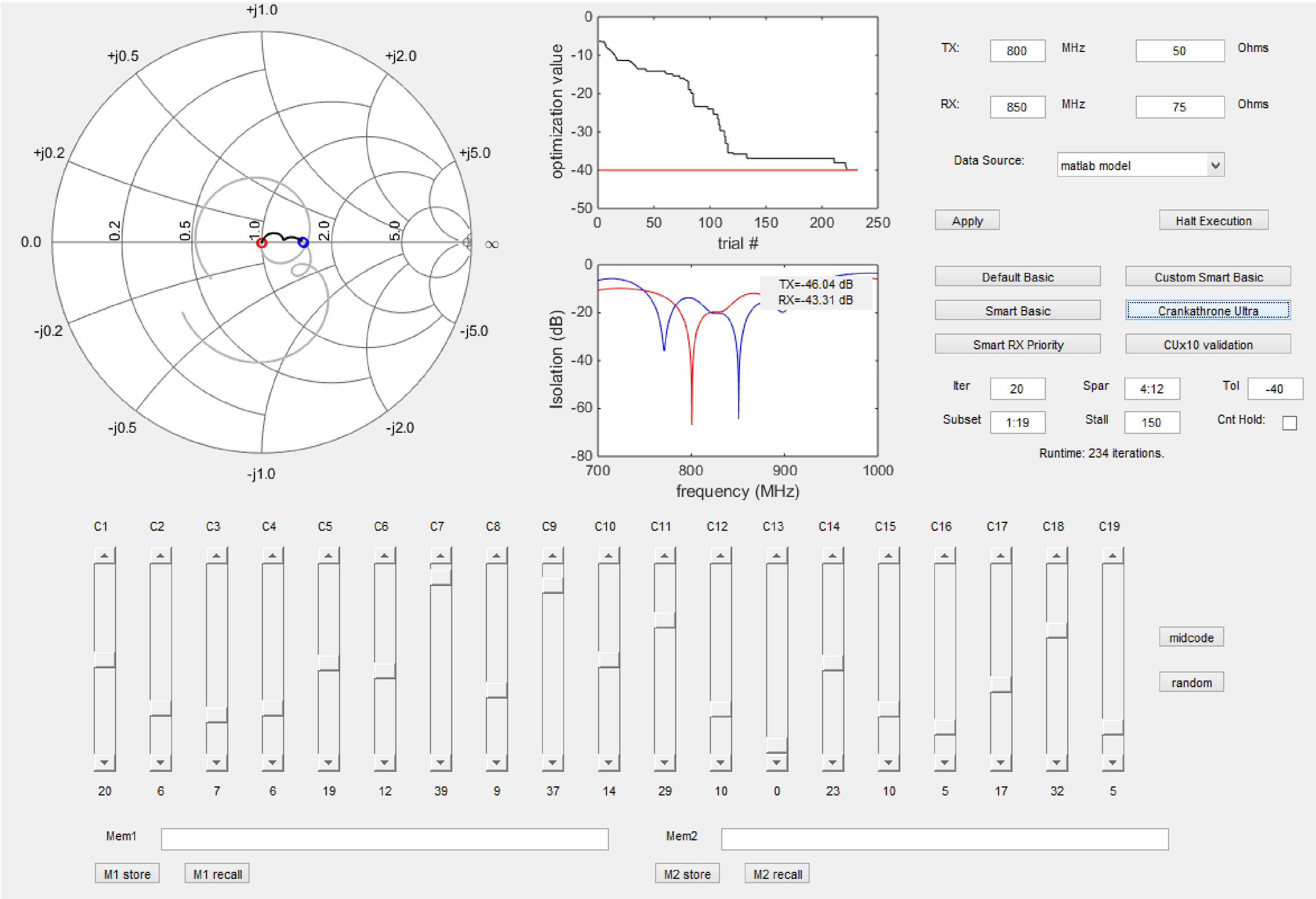


Band 19

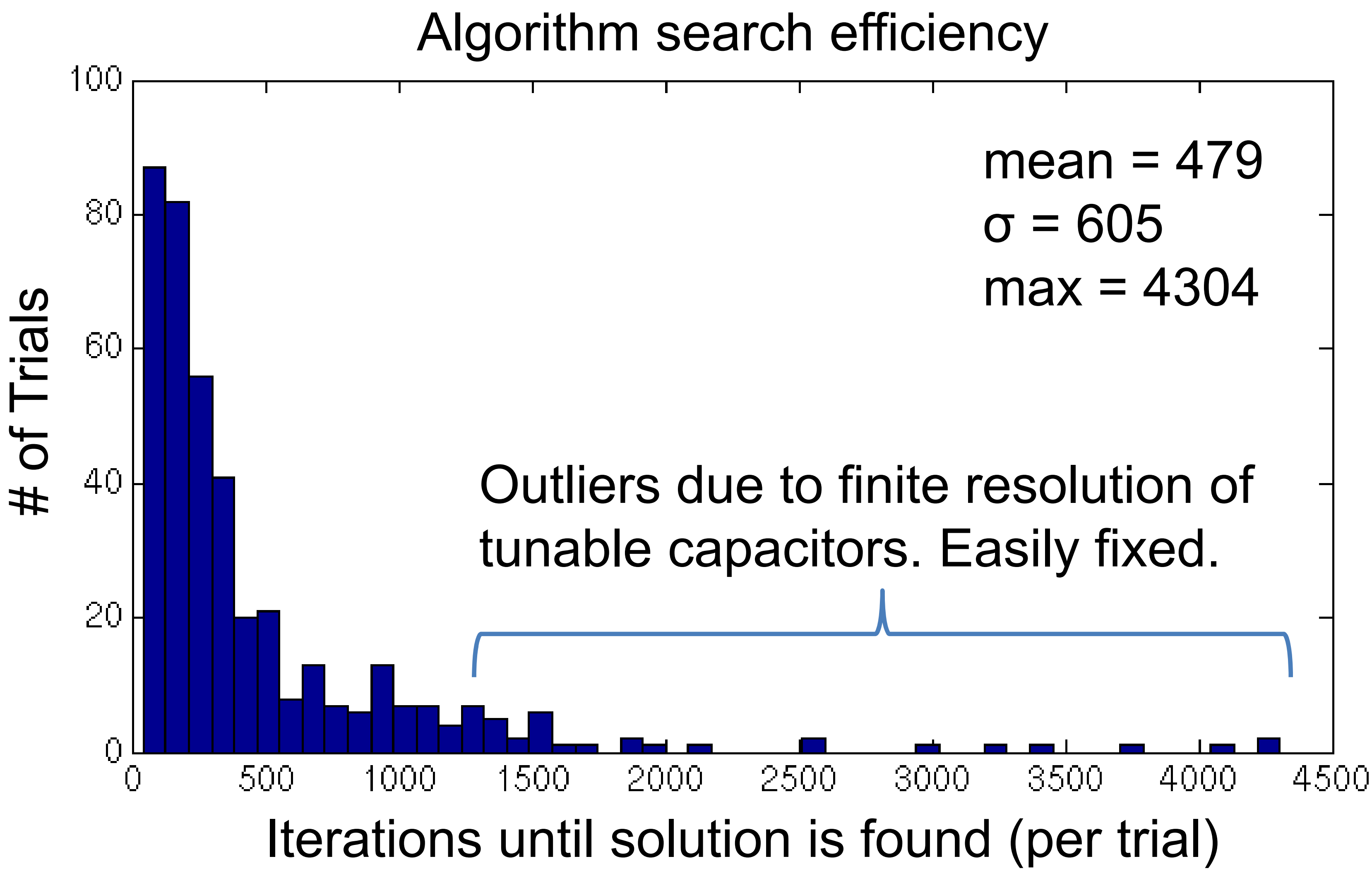


Band 20

Tuning Algorithm in Matlab



Tuning Efficiency Histogram



Conclusion

- First generic dual-frequency balance network
- Z_{ANT}/Z_{BAL} co-design specifications
  - $Region_{TX}$, $Region_{RX}$
- Efficient tuning algorithm demonstrated for search space of 2×10^{30}

ISSCC®

INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS • UNIVERSITY OF PENNSYLVANIA •