COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

IEEE

SSCS Distinguished Lecture

RF Circuit and System Innovations for a New Generation of Wireless Terminals

Peter R. Kinget

Analog & RF IC Design Research

Columbia Integrated Systems Laboratory
http://www.cisl.columbia.edu

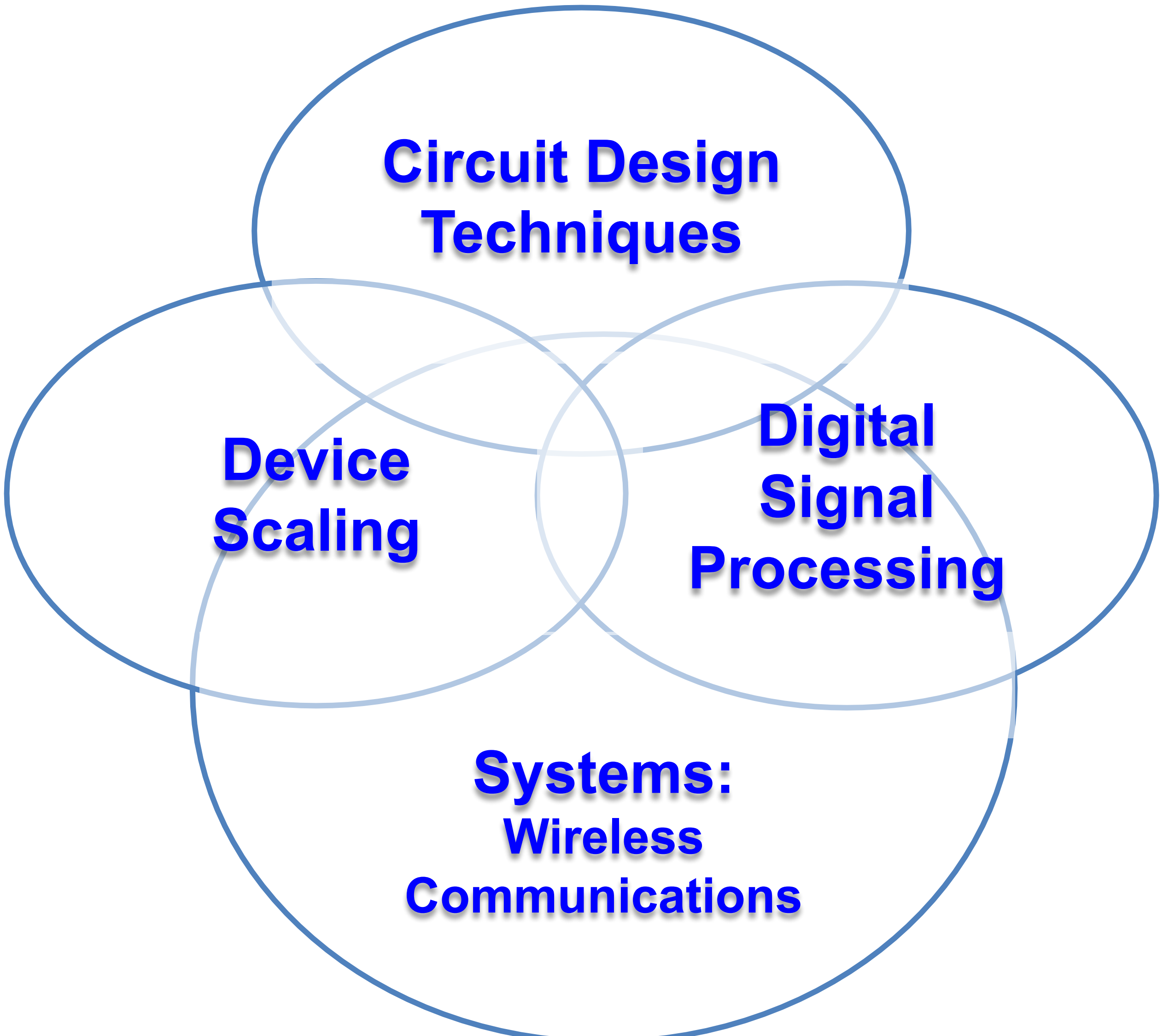
Outline

- *System* problem setting:

  The RF Spectrum Crunch

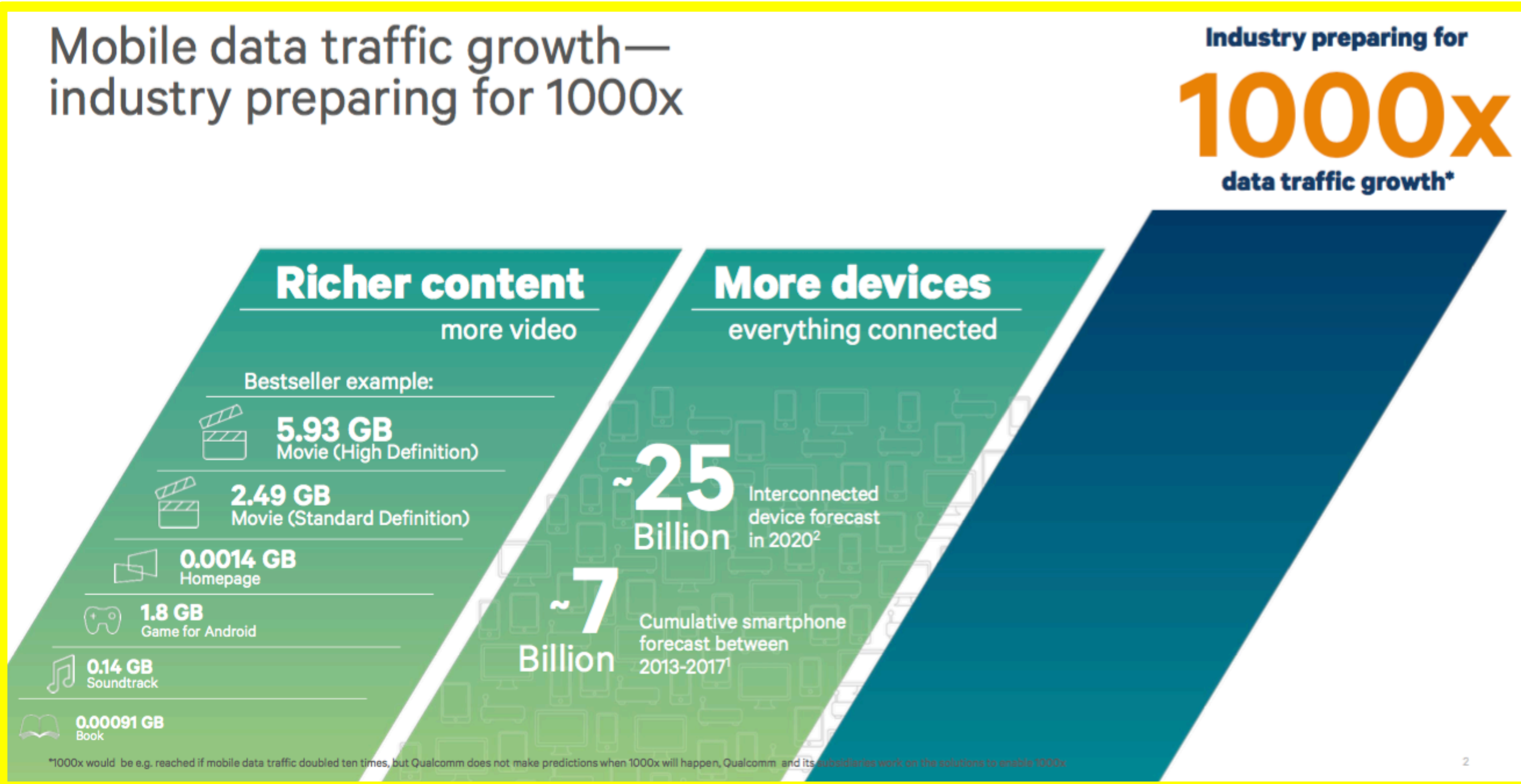
- *Circuit Solutions* enabled by *Device Scaling*
  - Field Programmable Receivers
  - Getting by with Switches and Capacitors …
- *Circuit Solutions* assisted by *Digital Signal Processing*
  - Compressive Sampling for RF Spectrum Scanning
- Conclusions

"Underlying Theme"
Crossing The Boundaries



“Data Storm”

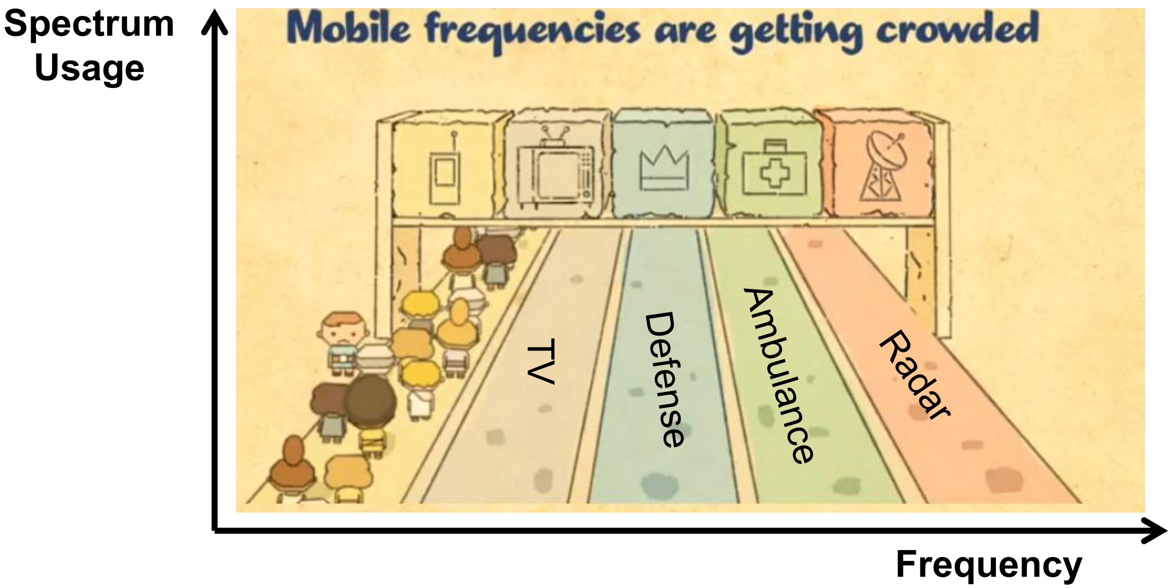
More Devices x More Content = 1,000x Data Storm



From: www.qualcomm.com/1000x

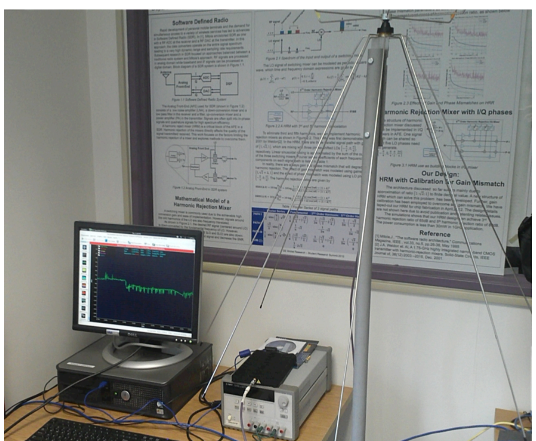
Artificial Spectrum Scarcity

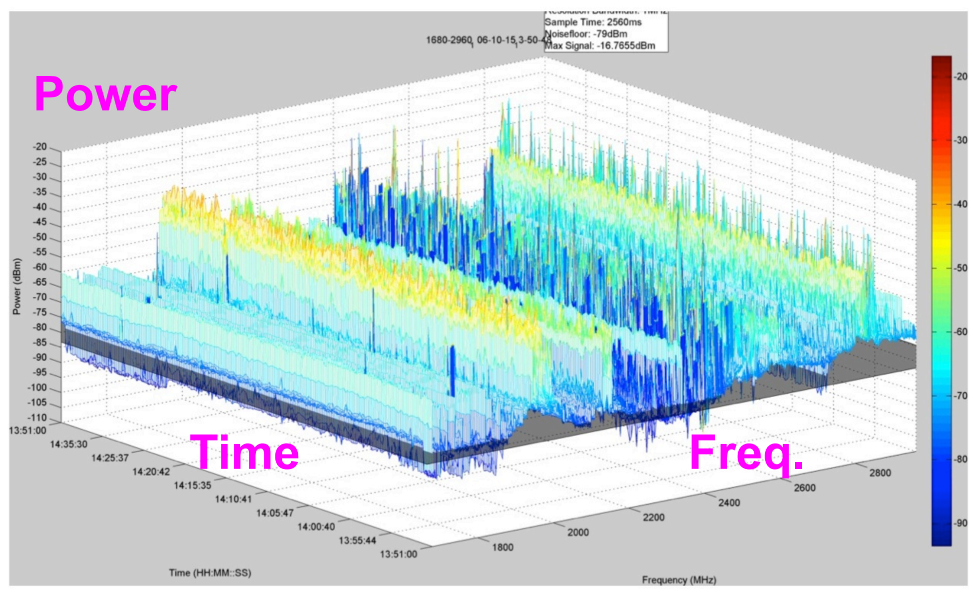
Today's Wireless Communications



Source: Nokia

Spectrum Measurements
in New York City

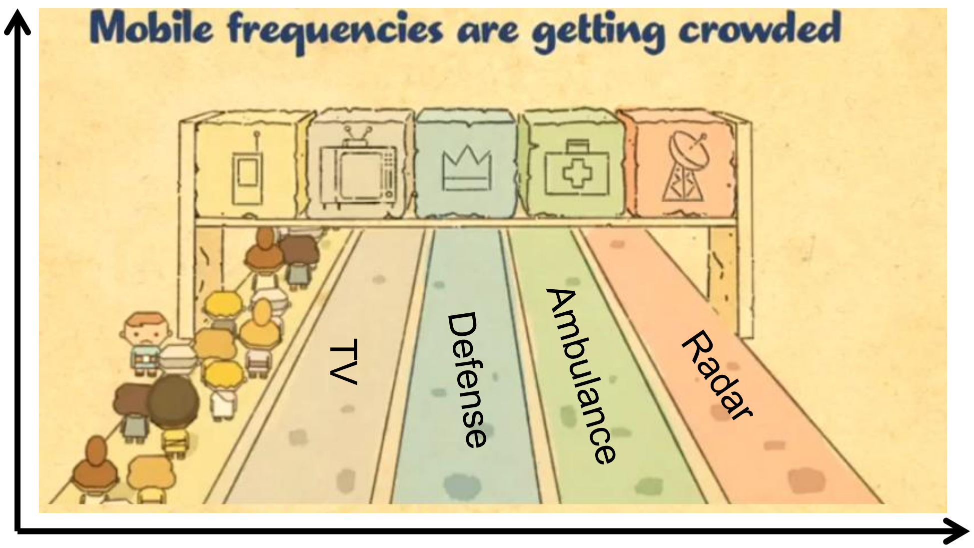




Overcoming the Artificial Spectrum Scarcity

Today's Wireless Communications

Spectrum Usage



Source: Nokia

Frequency

Next-Generation Wireless Communications

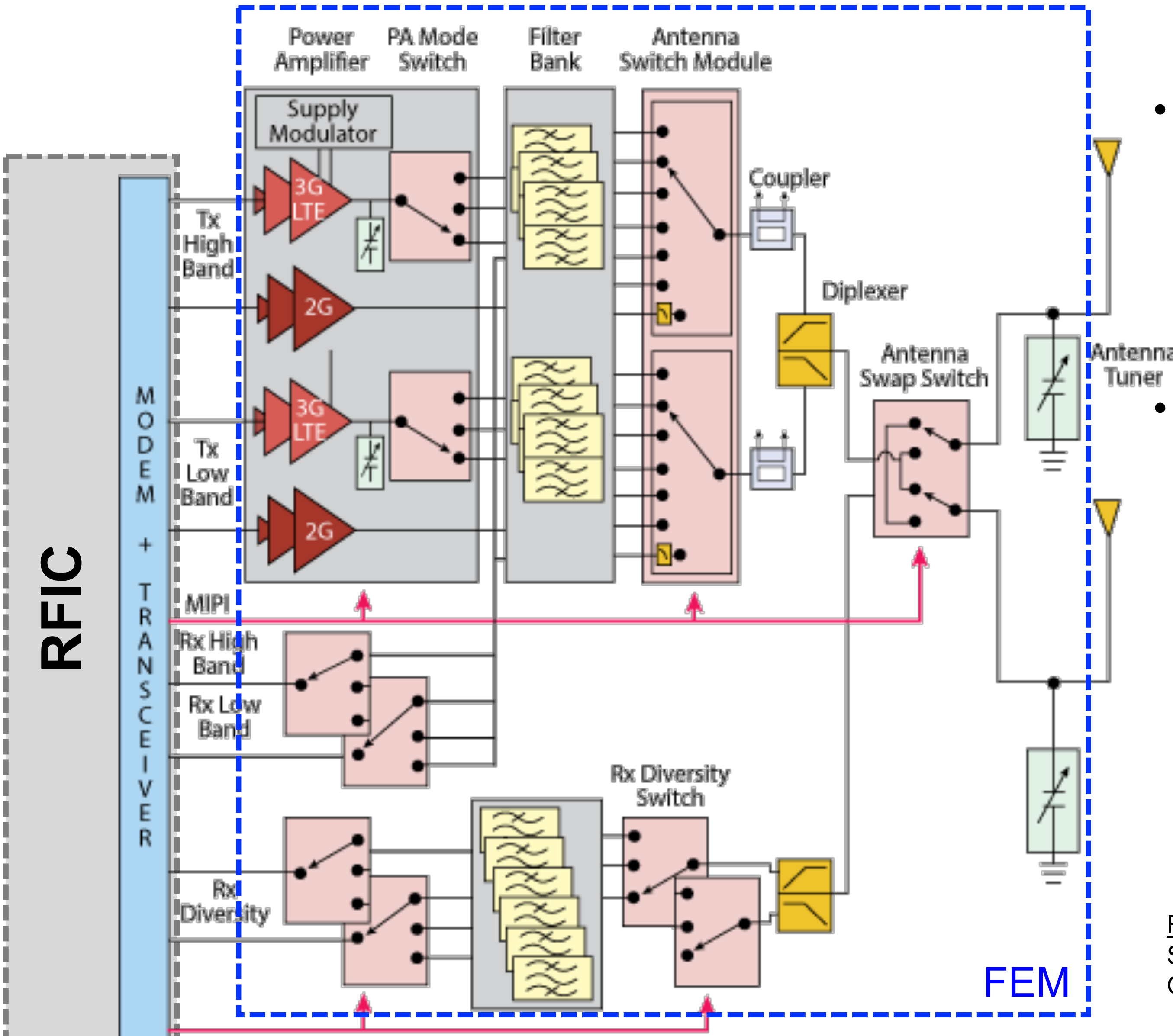
Spectrum Usage

Frequency

Cognitive Radio

- ✓ Dynamic
- ✓ Opportunistic
- ✓ Adaptive
- ✓ Spectrum Aware

Modern Mobile Phone

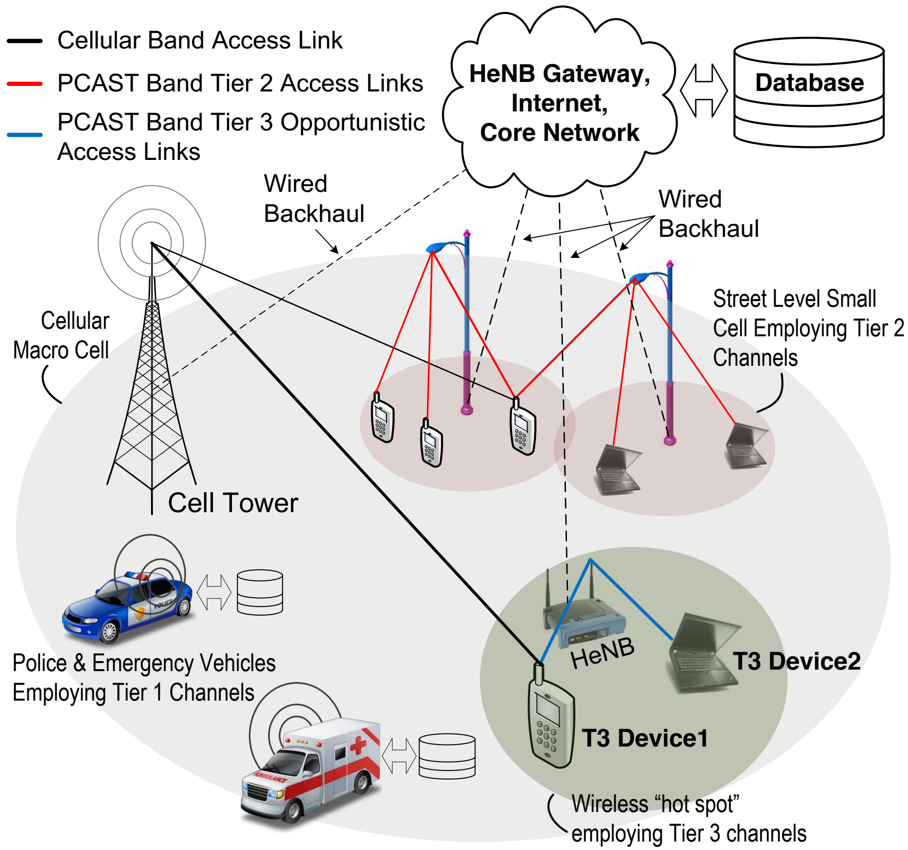


- Complex Antenna Front-End Module (FEM) with RF switches, SAW filter banks & P/As
- Support for
  - Large Freq. Range
  - Large # Bands (e.g., >46 in LTE)
  - Carrier Aggregation

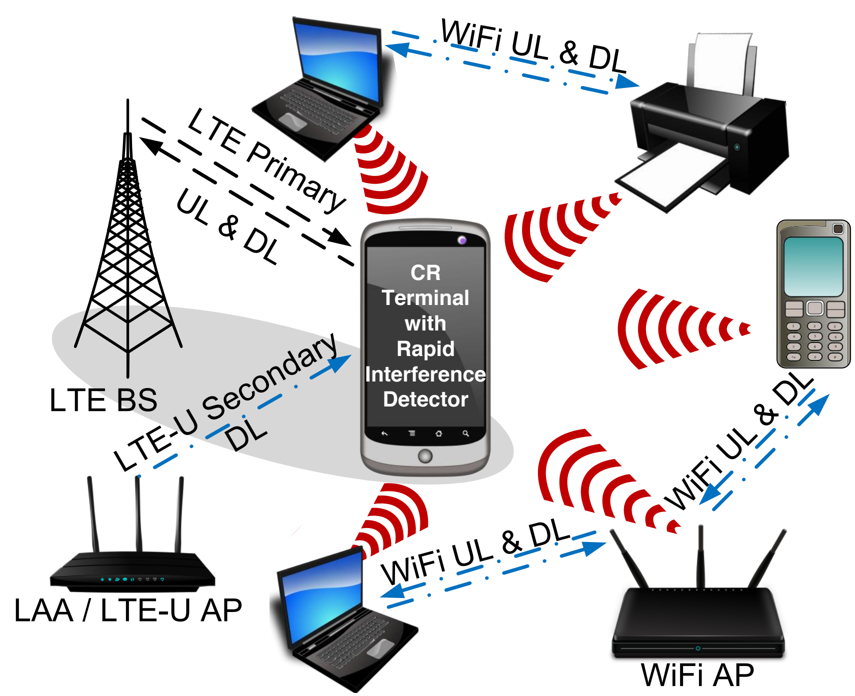
From: "RF SOI: Revolutionizing RF System Design," *Microwave Journals*, Oct. 2015

Examples of Next Generation Wireless Systems

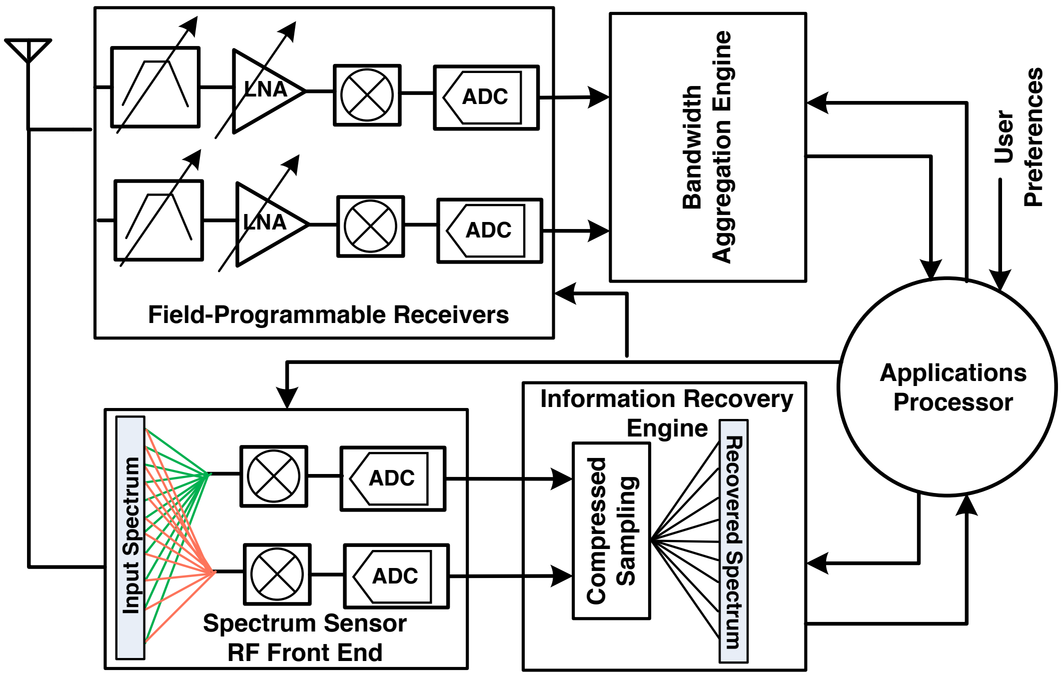
Multi-Tier Systems in PCAST Band

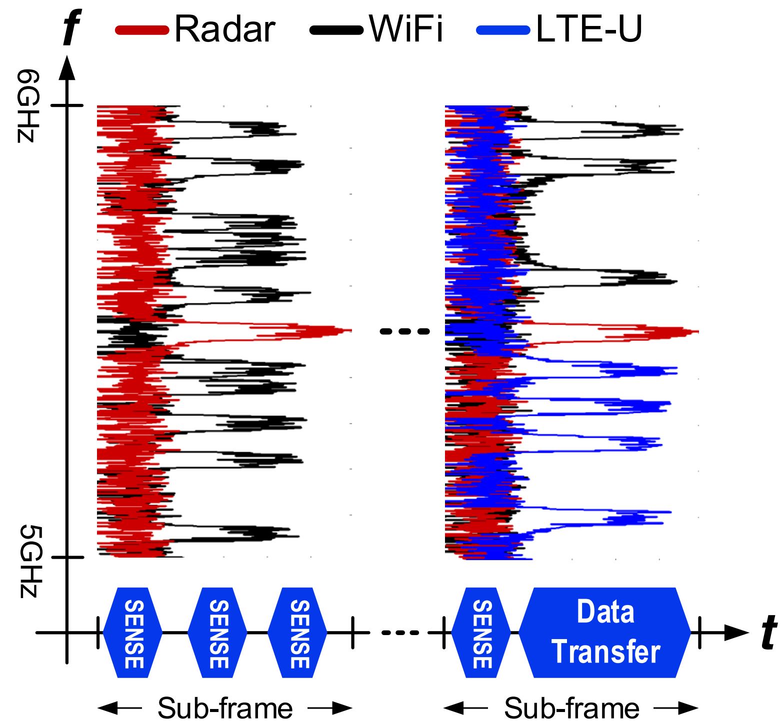


Combining Licensed & Unlicensed Spectrum (LTE-U)



“Next-Generation” Receiver





- Next-generation receivers need:
  - ❖ **Field programmability** – avoid worst-case design strategy
  - ❖ **Wideband Operation & out-of-band blocker tolerance** with limited off-chip filtering
  - ❖ Fast & Low power & Wideband **Spectrum Sensing**

Desired Circuit Innovations

- Highly Flexible Circuits
  - programmable operation: f_0, BW, NF, IIP_3, P
- Simplified Antenna FEM
  - SW-Cap RF Front End
- Spectral Awareness
  - Compressive Sampling based Spectrum Scanning

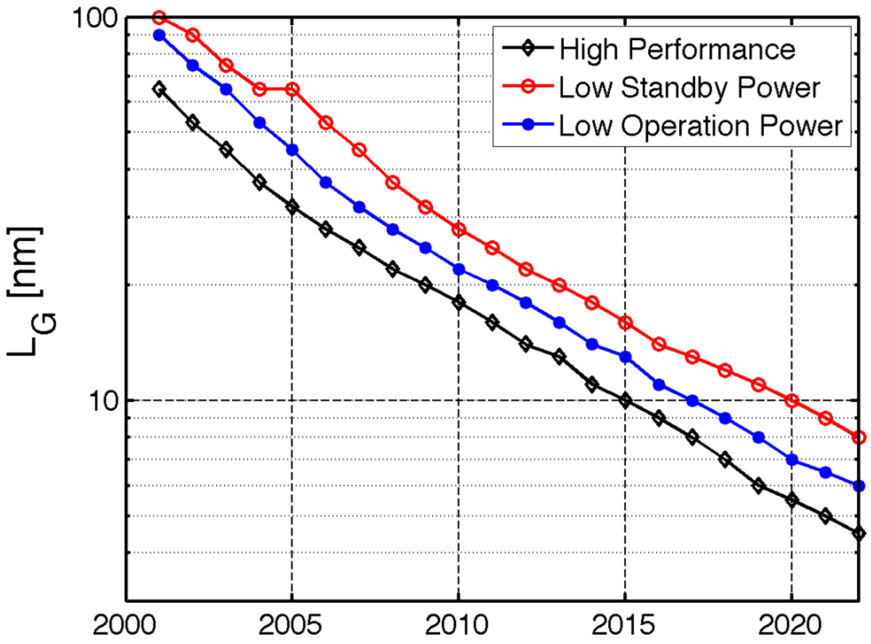
Circuit Techniques

Device Scaling

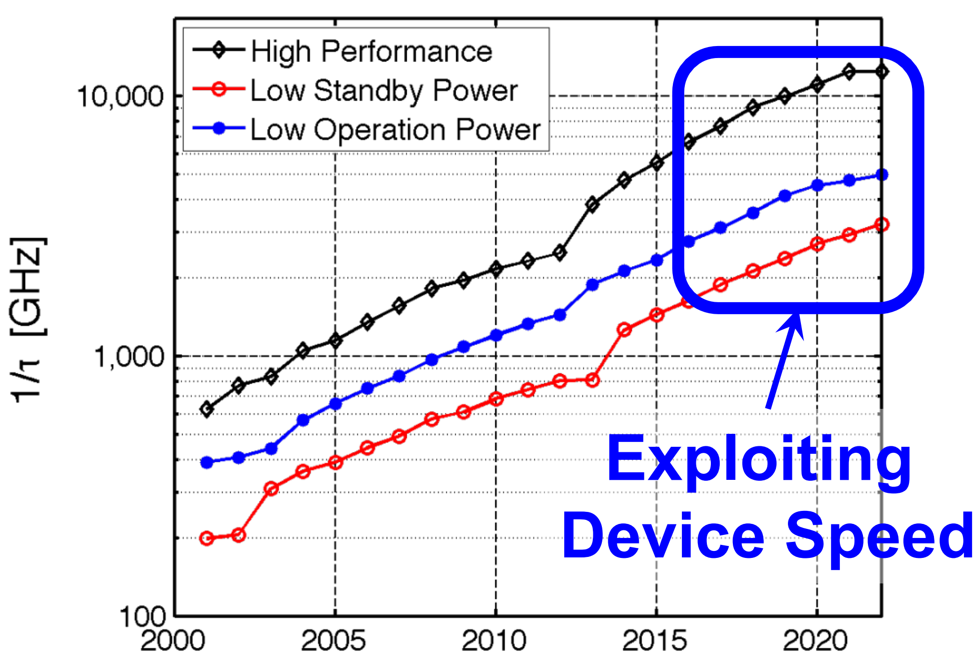
Signal Processing

CMOS Device Scaling

Device Gate Length



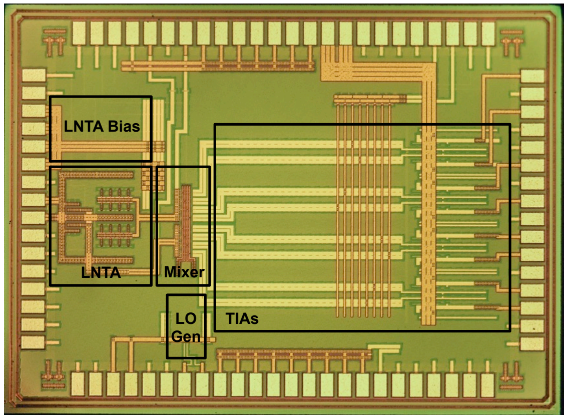
Device Switching Speed



Device density & speed ↑

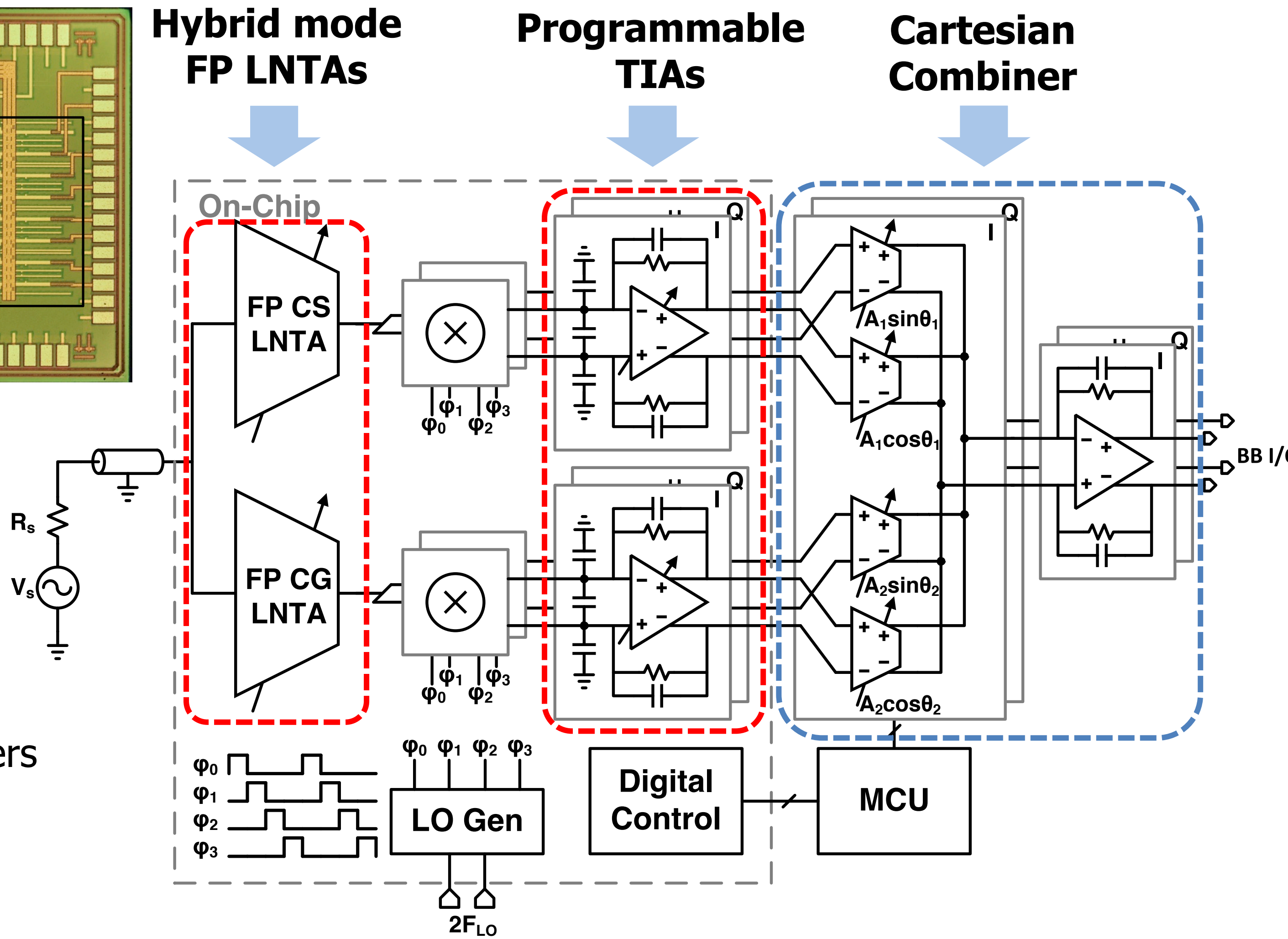
From: ITRS CMOS Roadmap

Field-Programmable Receiver with Hybrid Class-AB-C LNTAs

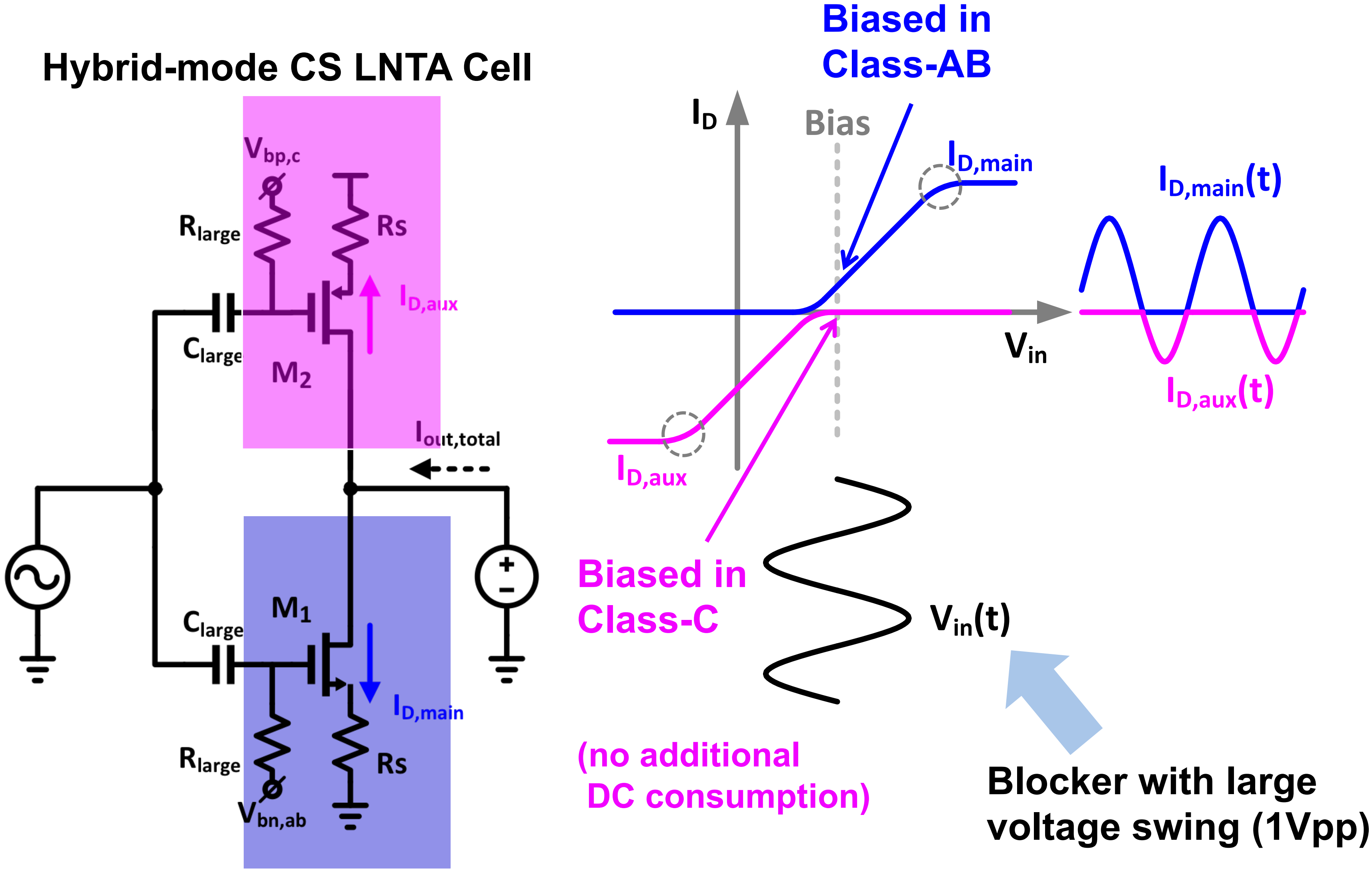


- 40nm CMOS LP technology
- 1.8mm x 1.3mm
- Active area: $1.6mm^2$

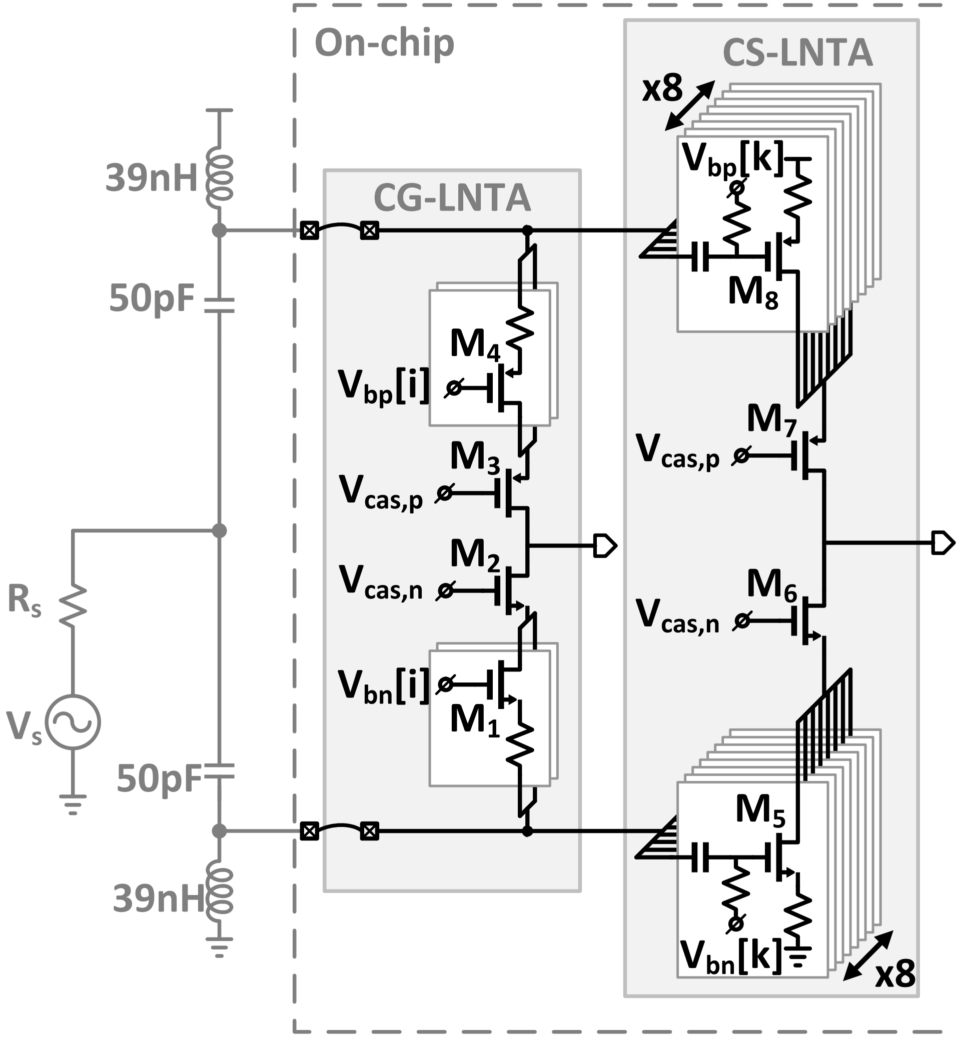
- Noise canceling Rx
- FP LNTAs and TIAs
- 4 phase passive mixers
- Cartesian based combiner



Hybrid Class-AB-C: Ultra-Linear LNTA



Field-Programmability for Hybrid Class-AB-C LNTAs



Mode		CG LNTAs 1	CG LNTAs 2	CS LNTAs 1	CS LNTAs 2	CS LNTAs 3	CS LNTAs 4	CS LNTAs 5	CS LNTAs 6	CS LNTAs 7	CS LNTAs 8
Low Noise Mode	P:	AB	C	AB	AB	AB	AB	AB	AB	AB	AB
	N:	C	AB	AB	AB	AB	AB	AB	AB	AB	AB
High Linearity Mode	P:	AB	C	AB	C	AB	C	AB	C	AB	C
	N:	C	AB	C	AB	C	AB	C	AB	C	AB
Low Power Mode	P:	AB	C	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
	N:	C	AB	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF

- CG-LNTA has 2 slices
- CS-LNTA has 8 slices
- Cascode transistors are shared
- Each transistor slice can be biased separately into class-AC, class-C or OFF

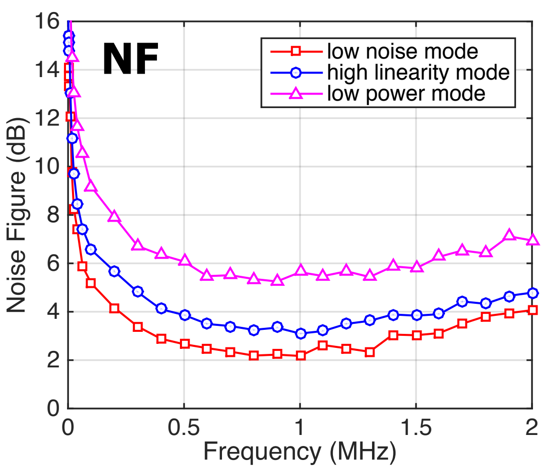
P:	C	AB	OFF
N:	C	AB	OFF

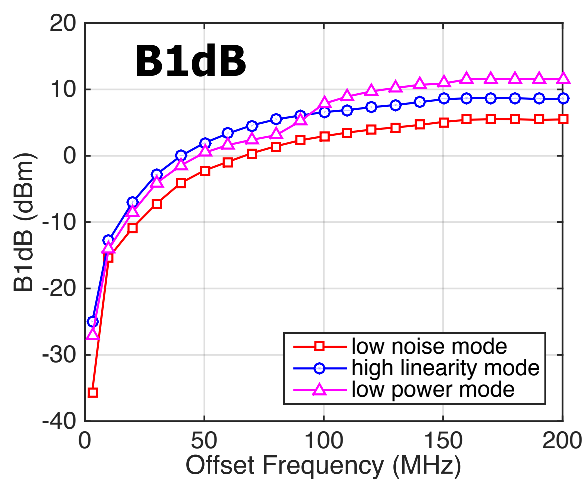
Field Programmable Performance Profile

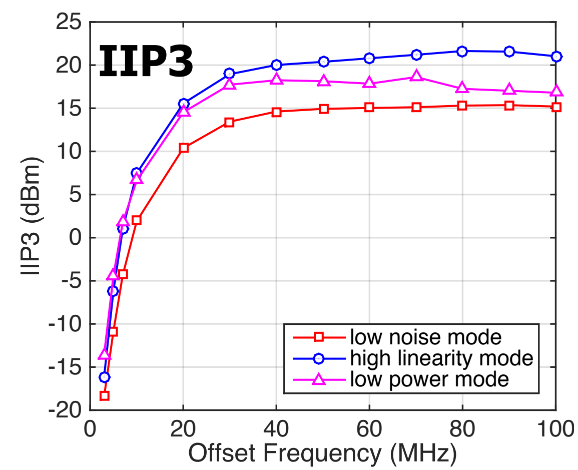
Measurements @f_{lo}=900MHz

Mode	Config (1–2)	Config (1–8)	NF	B_{1dB}	IIP_3	P_{DC}
Low NF Mode	P: AB C N: C AB	P: AB AB AB AB AB AB AB AB N: AB AB AB AB AB AB AB AB	Low ☺ (2.2dB)	Moderate (+5dBm)	Moderate (+15dBm)	High ☹ (49mA)
High Linearity Mode	P: AB C N: C AB	P: AB C AB C AB C AB C N: C AB C AB C AB C AB	Moderate (3dB)	High ☺ (+8.5dBm)	High ☺ (+21dBm)	Moderate (42mA)
Low Power Mode	P: AB C N: C AB	P: OFF OFF OFF OFF OFF OFF OFF OFF N: OFF OFF OFF OFF OFF OFF OFF OFF	High ☹ (5.5dB)	High ☺ (+11dBm)	High ☺ (+17dBm)	Low ☺ (20mA)

Measured Performance







Desired Circuit Innovations

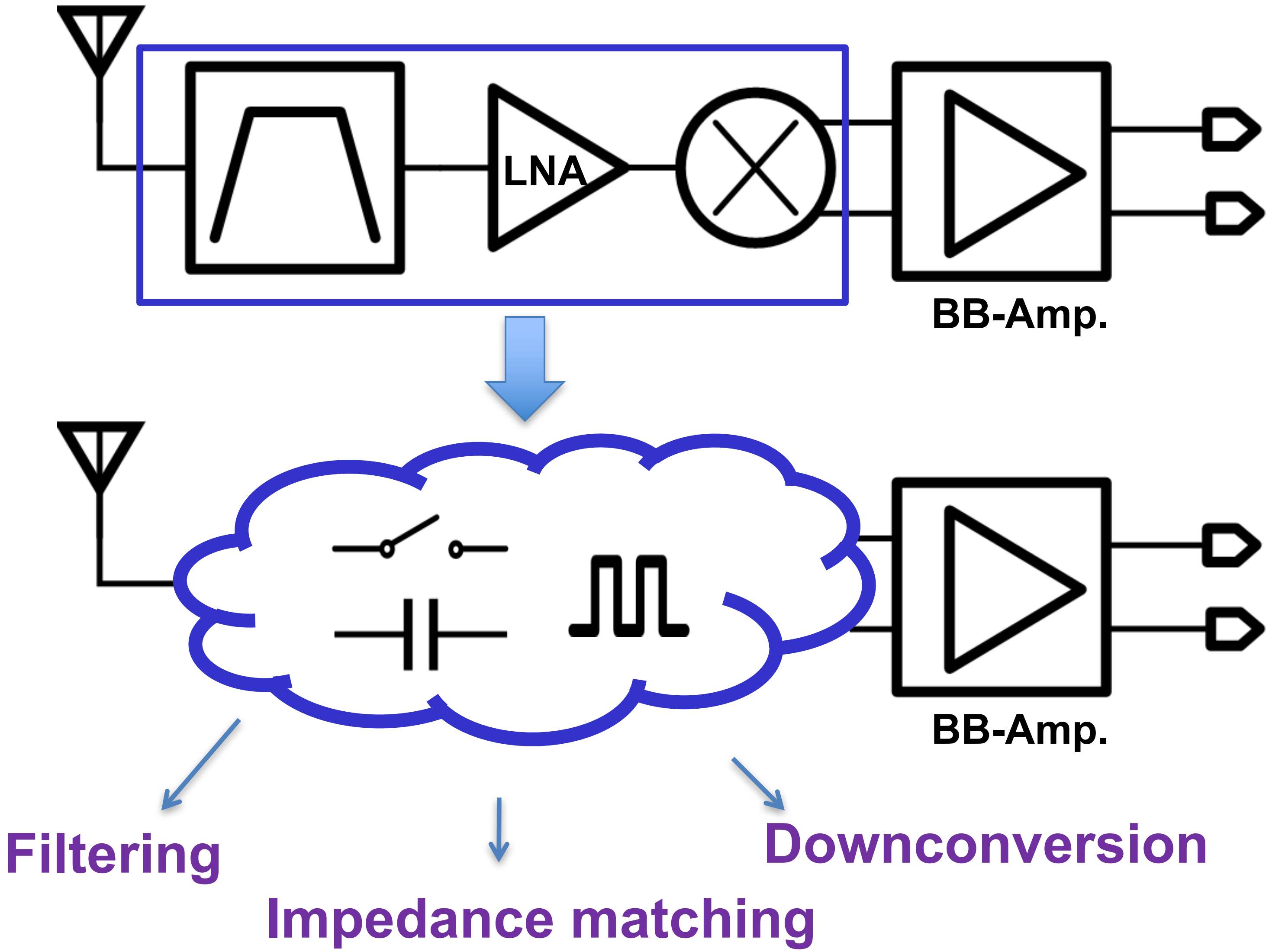
- Highly Flexible Circuits
  - programmable operation: f_0, BW, NF, IIP_3, P
- Simplified Antenna FEM
  - SW-Cap RF Front End
- Spectral Awareness
  - Compressive Sampling based Spectrum Scanning

Circuit Techniques

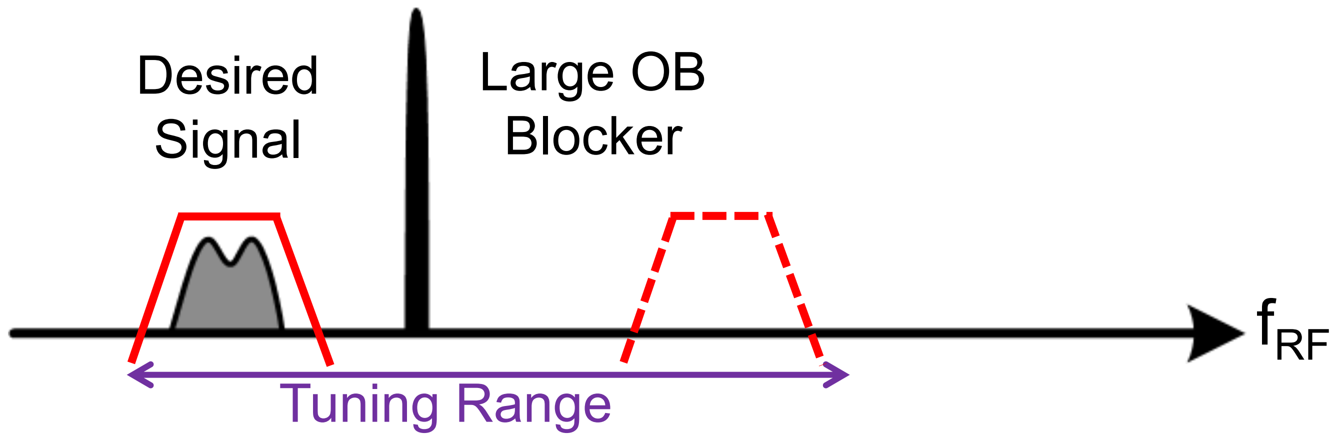
Device Scaling

Signal Processing

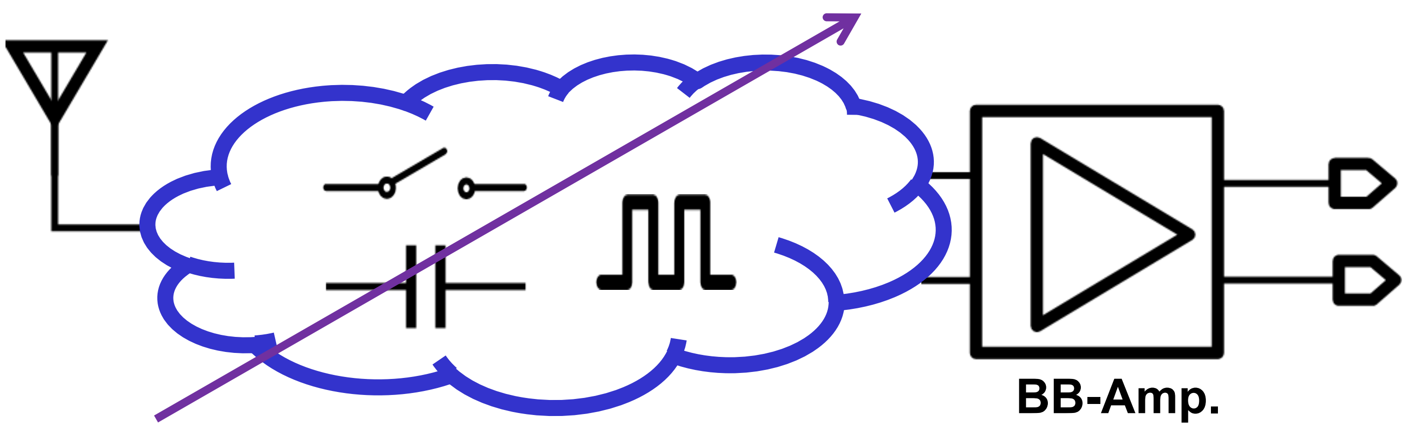
RF Front End with Only Switches & Capacitors



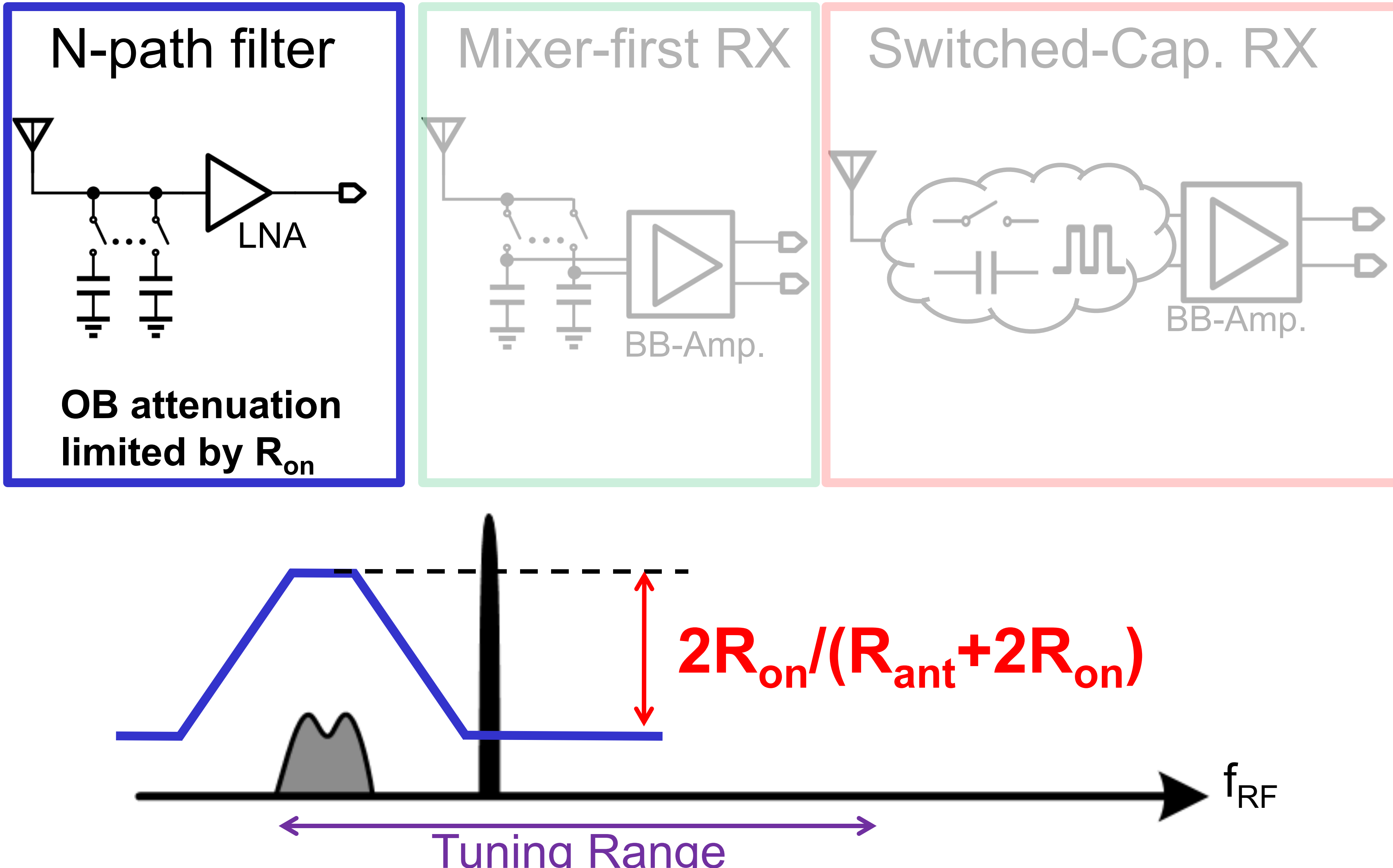
Switched-Capacitor RX with High Blocker Tolerance



High selectivity linear tunable filter is required for high blocker tolerance in reconfigurable RX

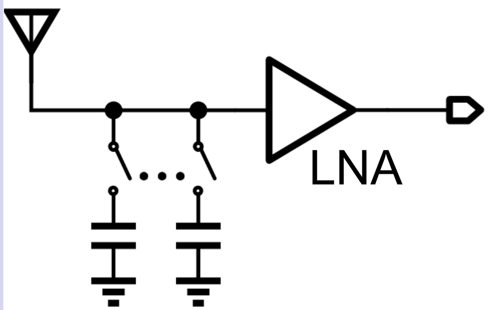


Blocker-Tolerant RX Design Solutions



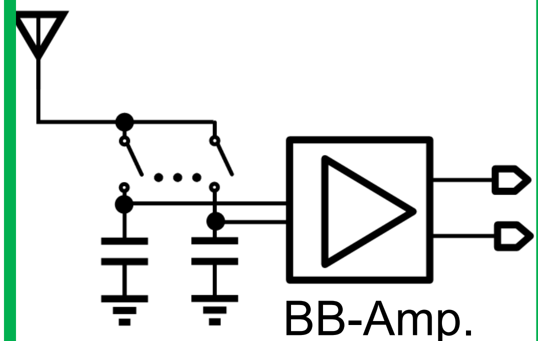
Blocker-Tolerant RX Design Solutions

N-path filter



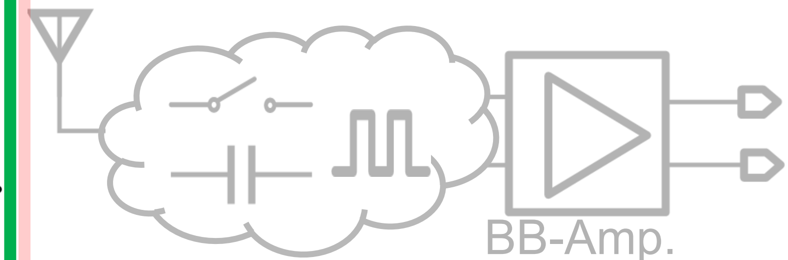
OB attenuation limited by R_{on}

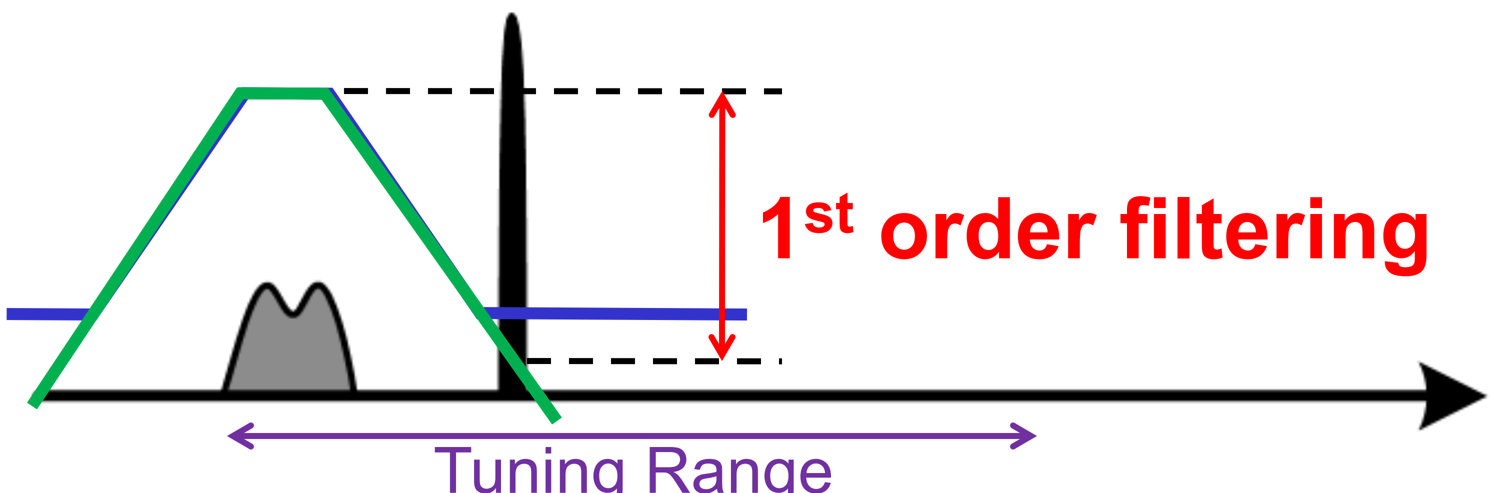
Mixer-first RX



Low filter order

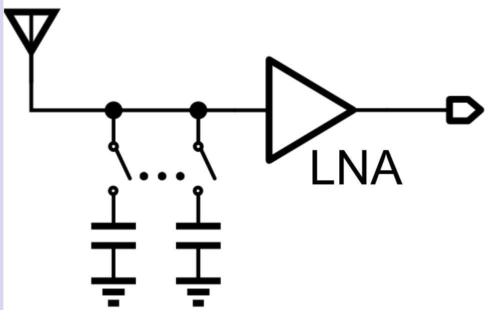
Switched-Cap. RX





Blocker-Tolerant RX Design Solutions

N-path filter



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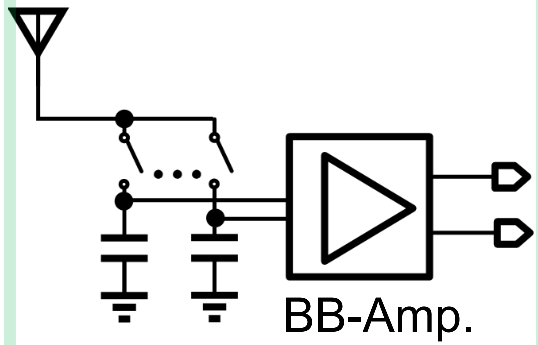
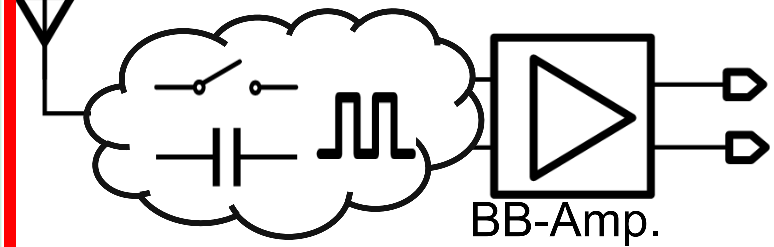
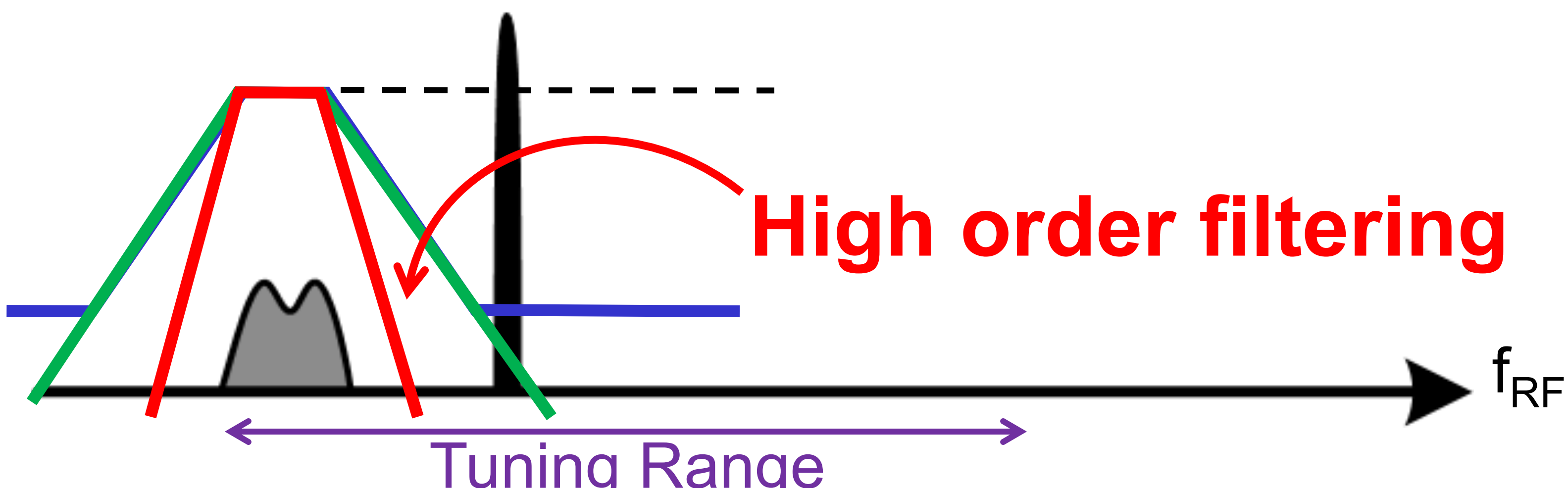


Low filter order

Switched-Cap. RX

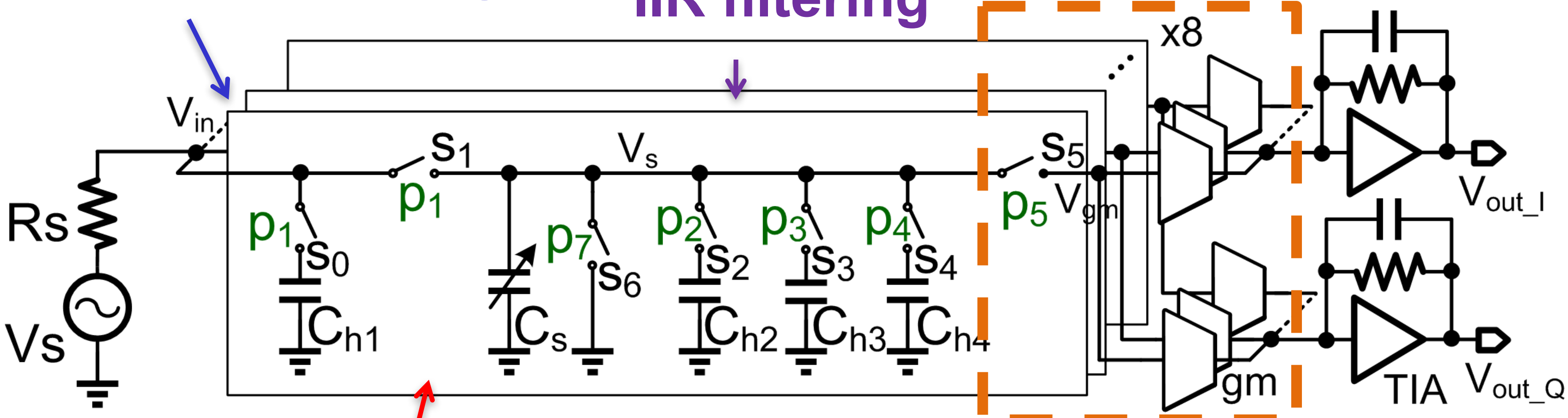




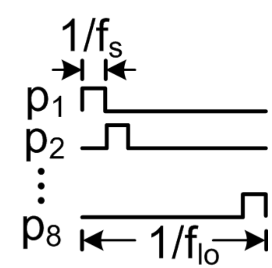
Switched-Cap. RF Front End

N-path filtering

DT High order IIR filtering



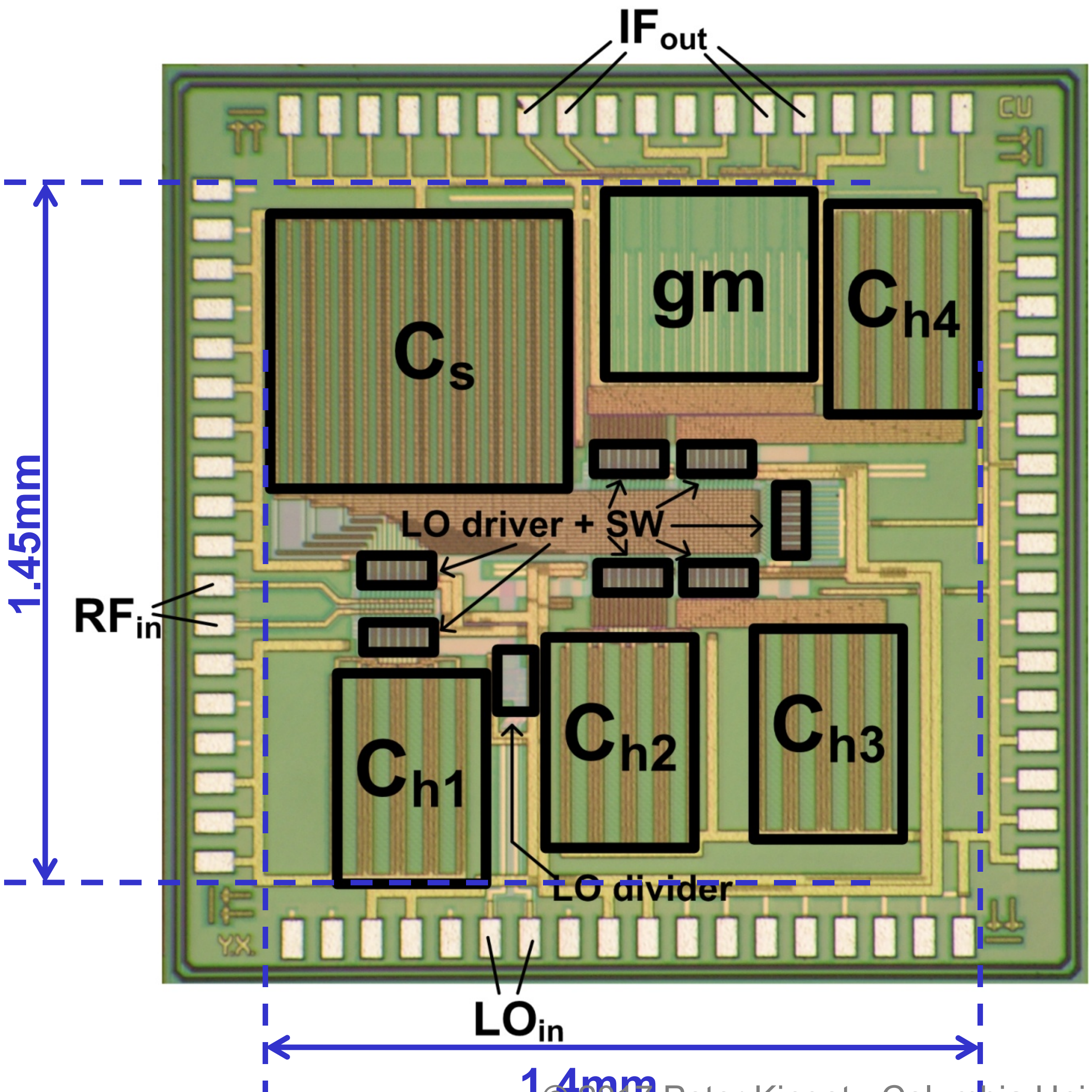
Impedance matching
Sampling



N-path filtering
Impedance matching and sampling
$f_s=8f_{lo}$
High order DT IIR filtering
Harmonic-rejecting downconversion

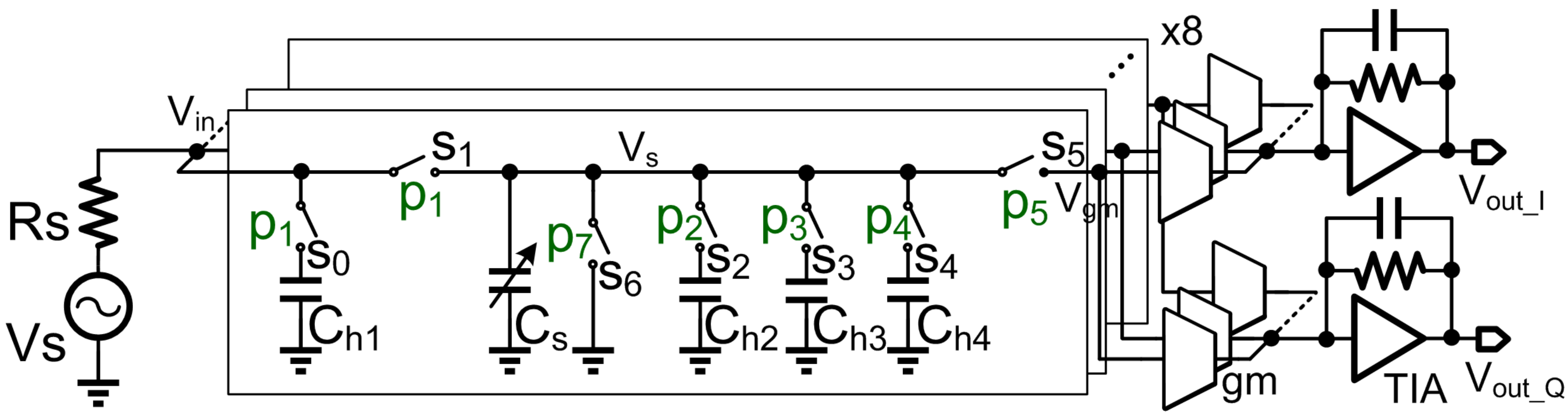
Harmonic-rejecting downconversion

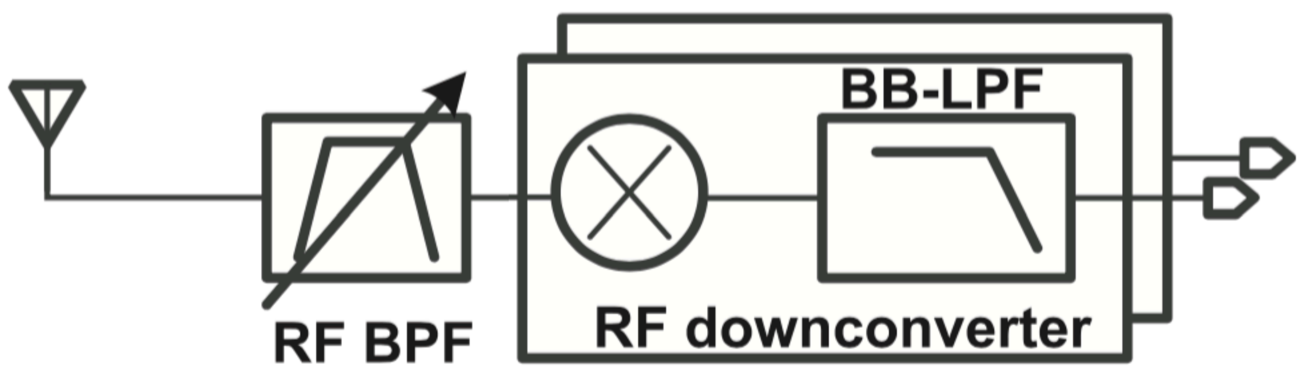
Switched-Cap RF Front End



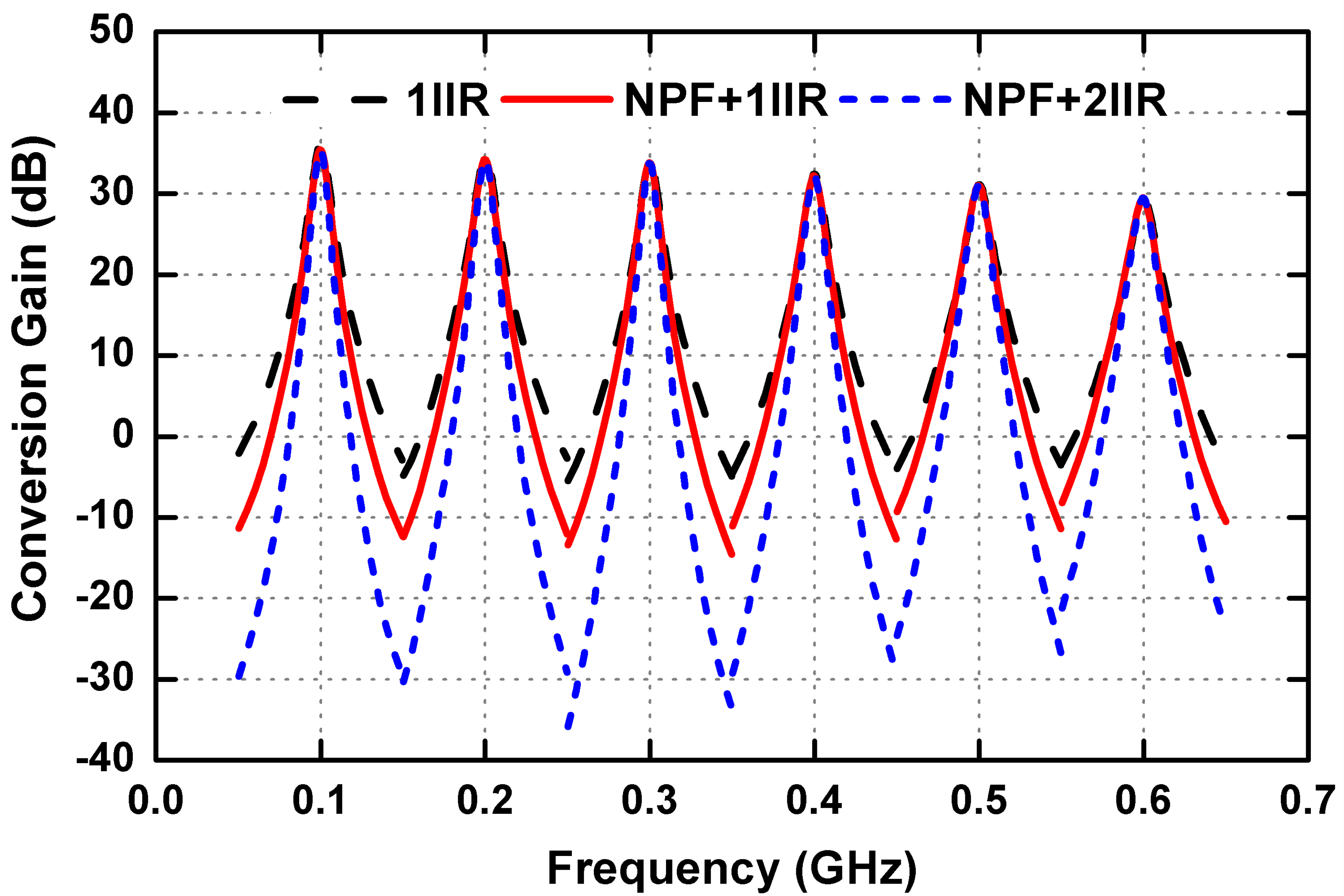
- Process:
  40nm LP CMOS
- Active Area:
  1.4mm x 1.45mm

Switched-Cap. RF Front End Functional Equivalence



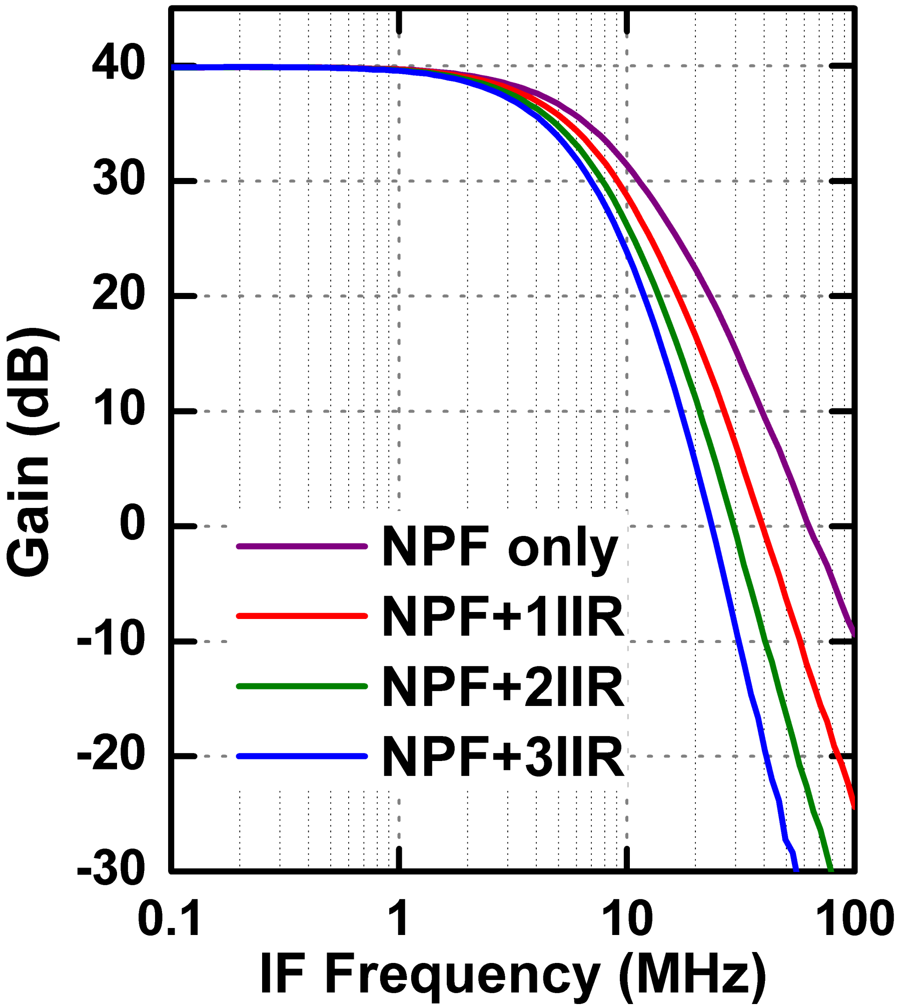


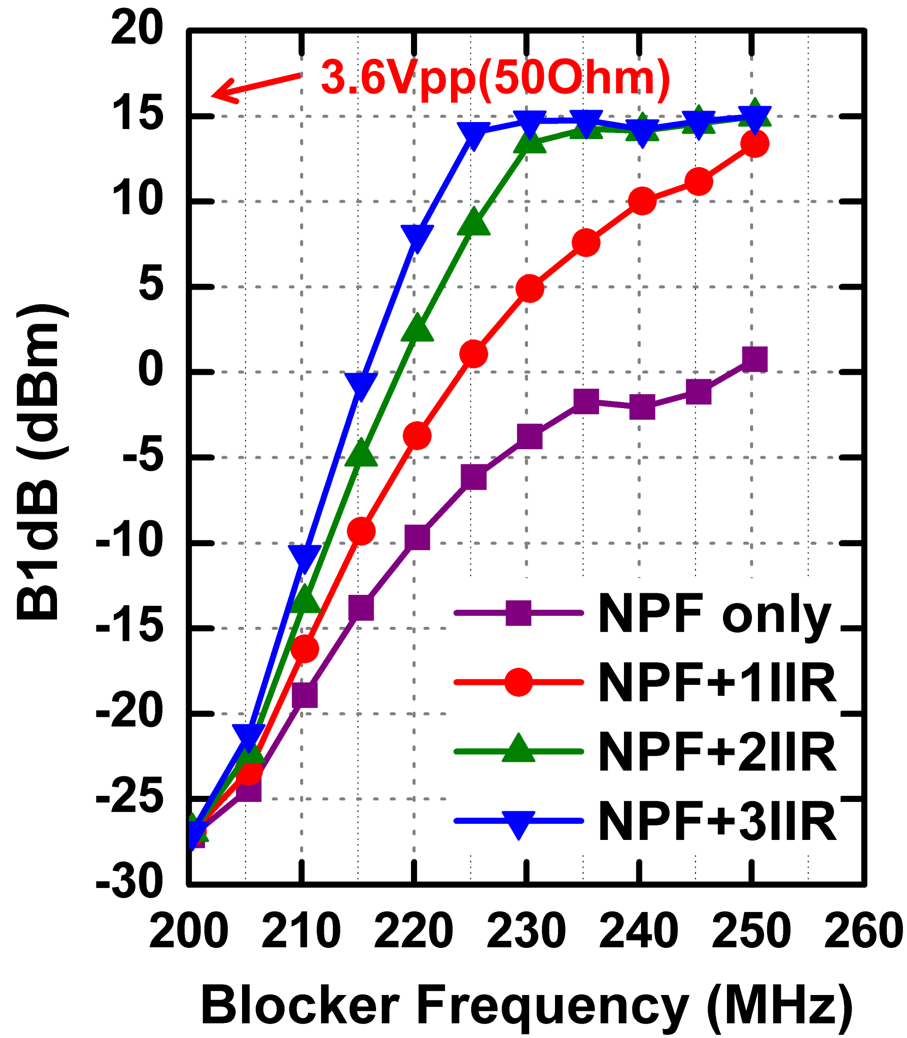
Conversion Gain



- Measured with 0.1-0.6GHz LO by 0.1GHz step

Conversion Gain & B1dB

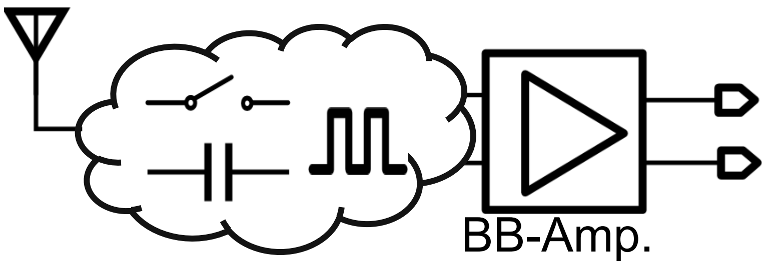




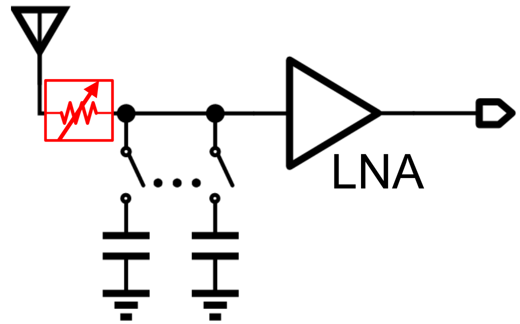
Measured at 200MHz LO frequency

Performance Comparison

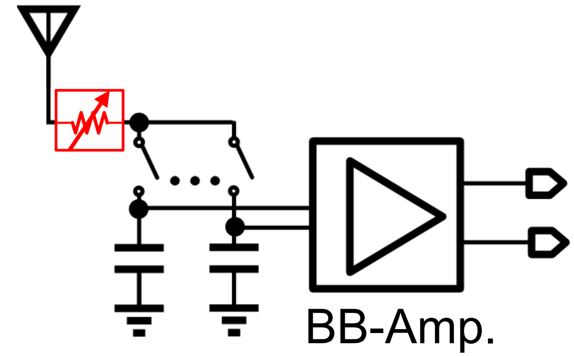
Switched-Cap. RX



N-path filter



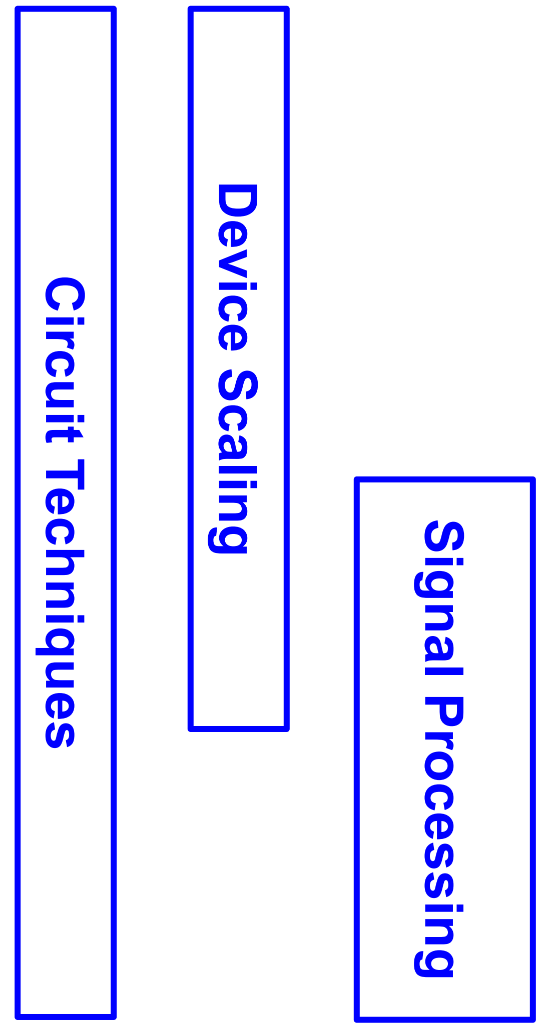
Mixer-first RX



	SCRX	N-path filter		Mixer-first RX	
	This work	[Darvishi-16]		[Andrews-10]	
Filter order before active circuits	**1-4**	1		1	
Attenuation (dB)	0	0	*8*	0	*10*
Max. B1dB (dBm)	**15**	7	*15*	5	*15*
Noise Figure (dB)	**6.8**	2.8	*10.8*	3.5	*13.5*

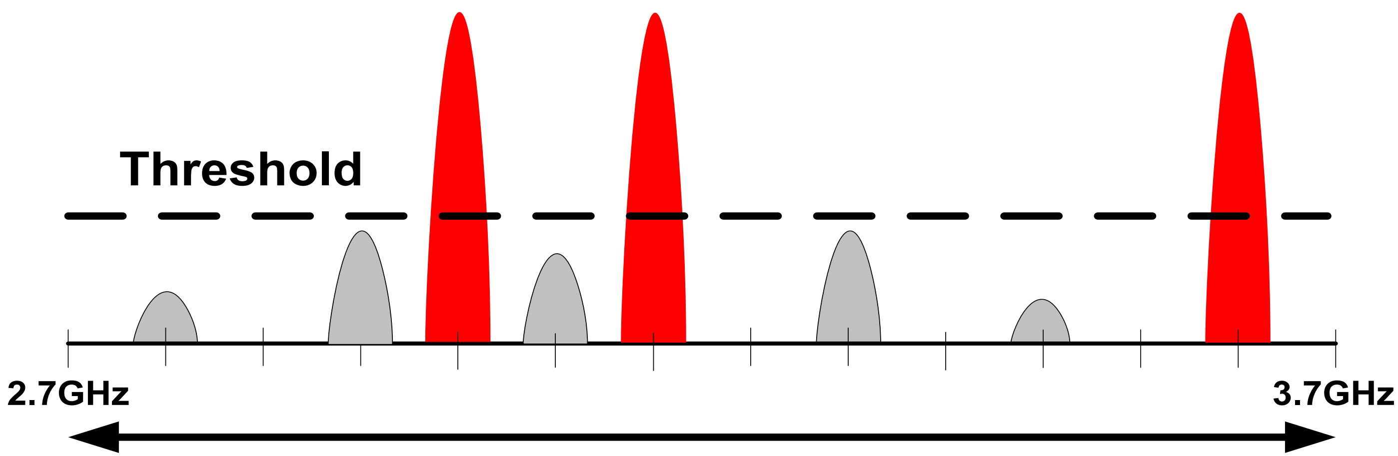
Desired Circuit Innovations

- Highly Flexible Circuits
  - programmable operation: f_0, BW, NF, IIP_3, P
- Simplified Antenna FEM
  - SW-Cap RF Front End
- Spectral Awareness
  - Compressive Sampling based Spectrum Scanning



"1D Spectrum Image"

PCAST Band 2.7-3.7GHz

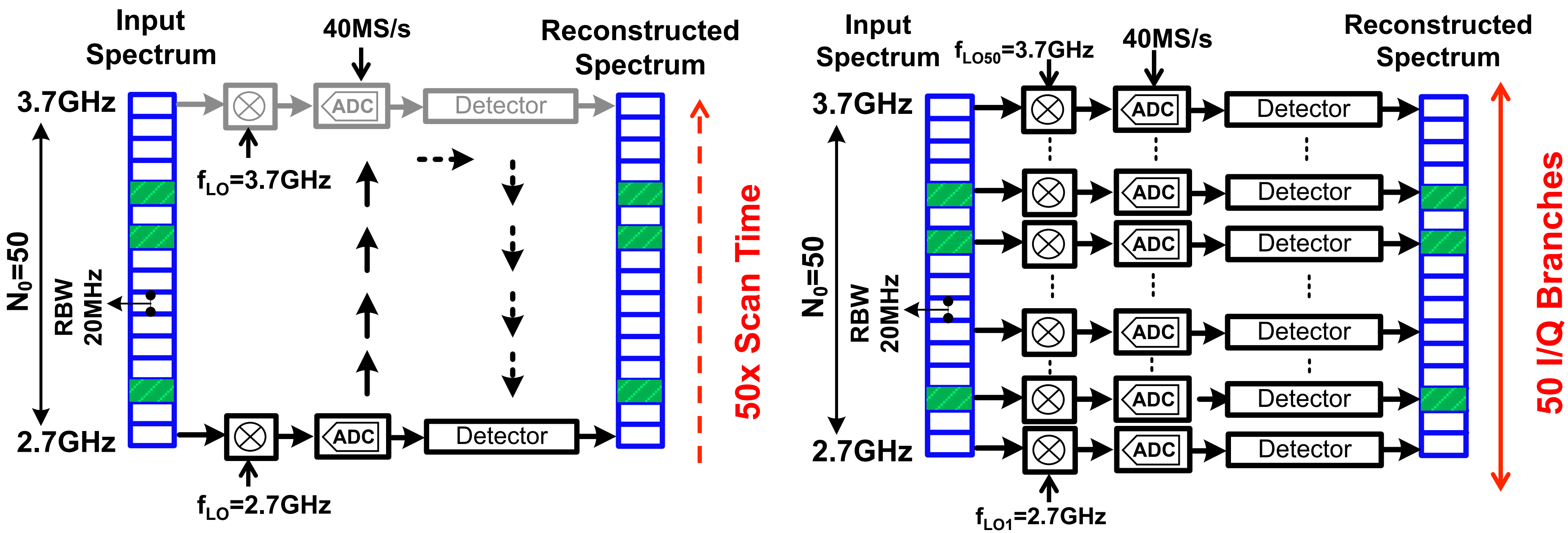


Active interferers K_0=3, N_0=50

Sparse and Dynamic Spectrum

K_0: Number of active interferers (supports)
N_0: Number of bins

Traditional Spectrum Scanner/Sensors



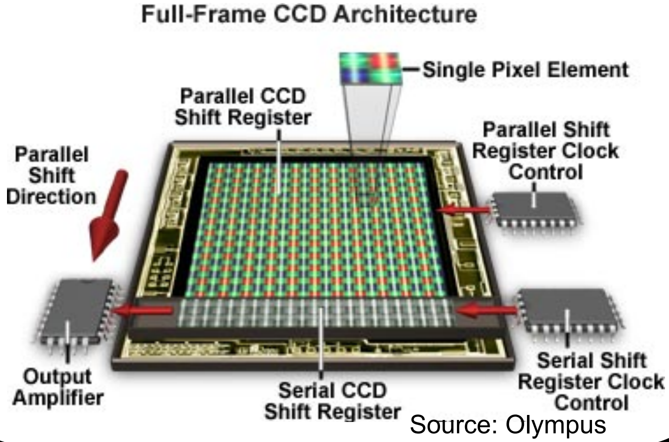
System Attributes	Sweeping Scanner	Multi-Branch Sensor
Scan Time	✗	✓
Power Consumption	✓	✗
Hardware Complexity	✓	✗

Energy Consumption = Scan Time x Power = Constant for both approaches

❖ **Fixed trade-off between Scan Time & Power**

Compressive Sampling (CS) to the Rescue

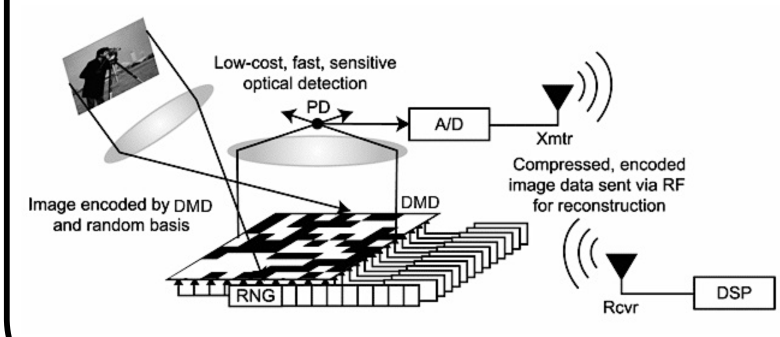
Multi-Pixel Camera



Source: Olympus

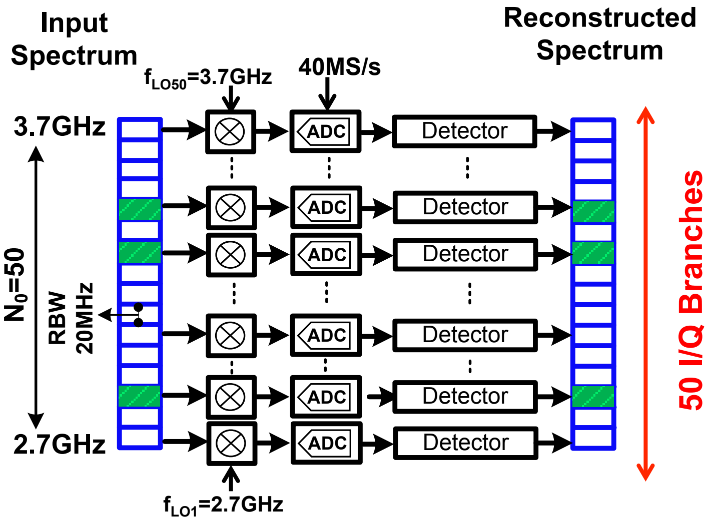
CS

Single-Pixel Camera



Source: Rice University

Traditional Multi-Branch Spectrum Sensor

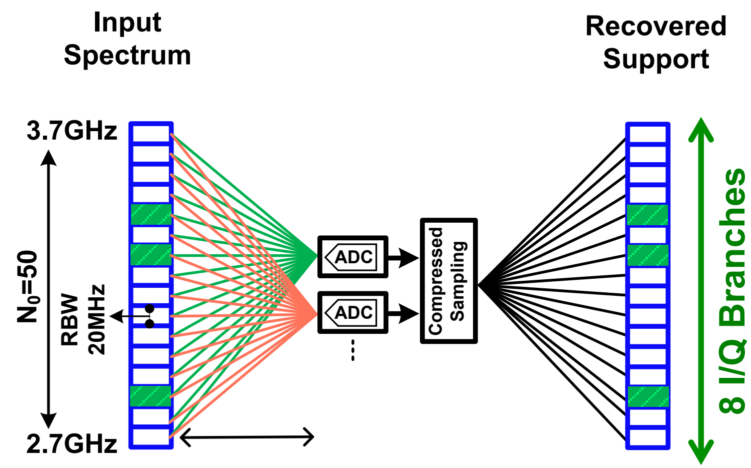


Fast but impractical

6.3× Compression

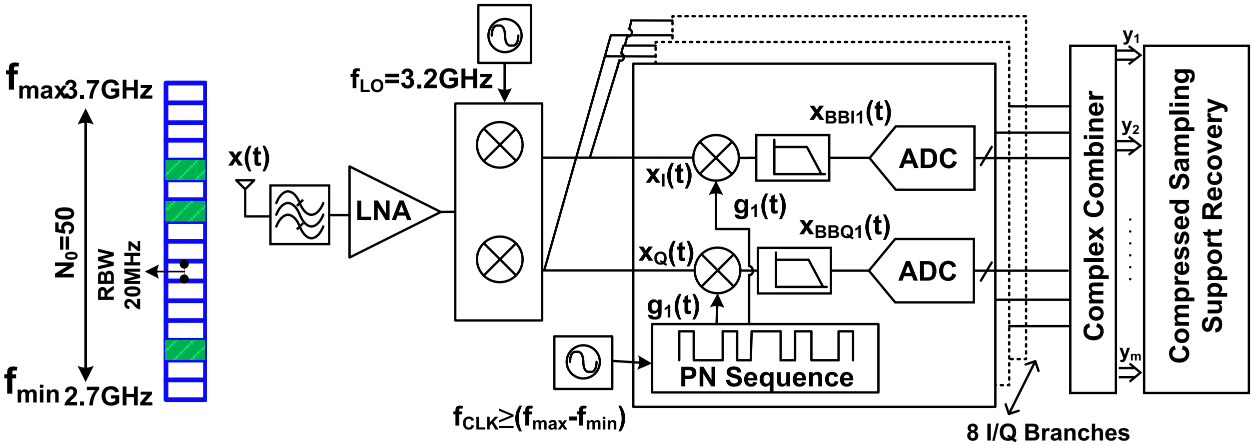
# of branches Aggregate sampling rate

"Snapshot of the Spectrum"

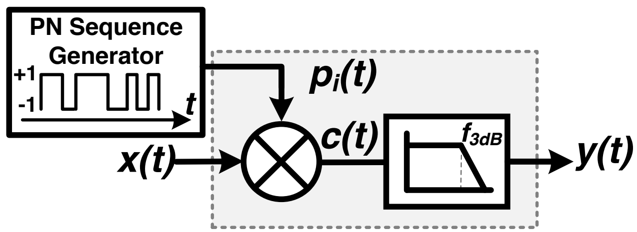


I/Q Downconversion & Pseudorandom Noise Seq. Mixing

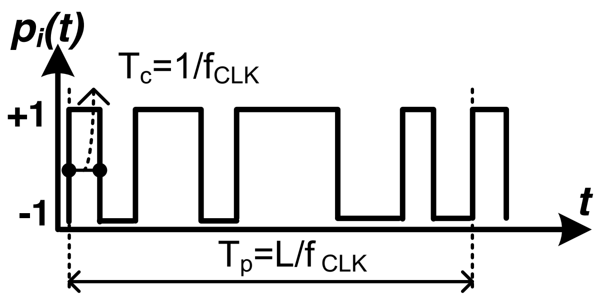
Quadrature Analog-to-Information Converter (QAIC)



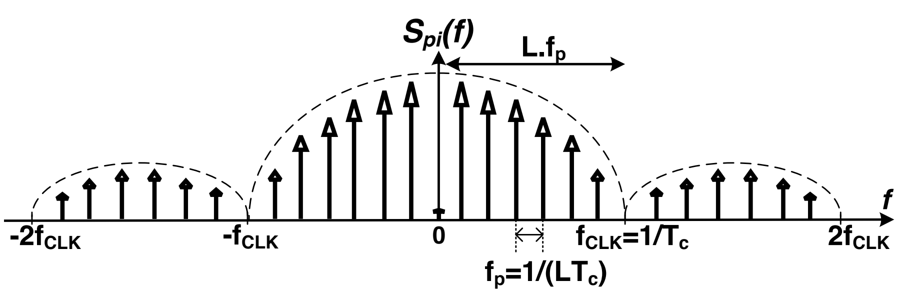
Analog Preprocessing for Compressive Sampling with Pseudorandom (PN) Sequences



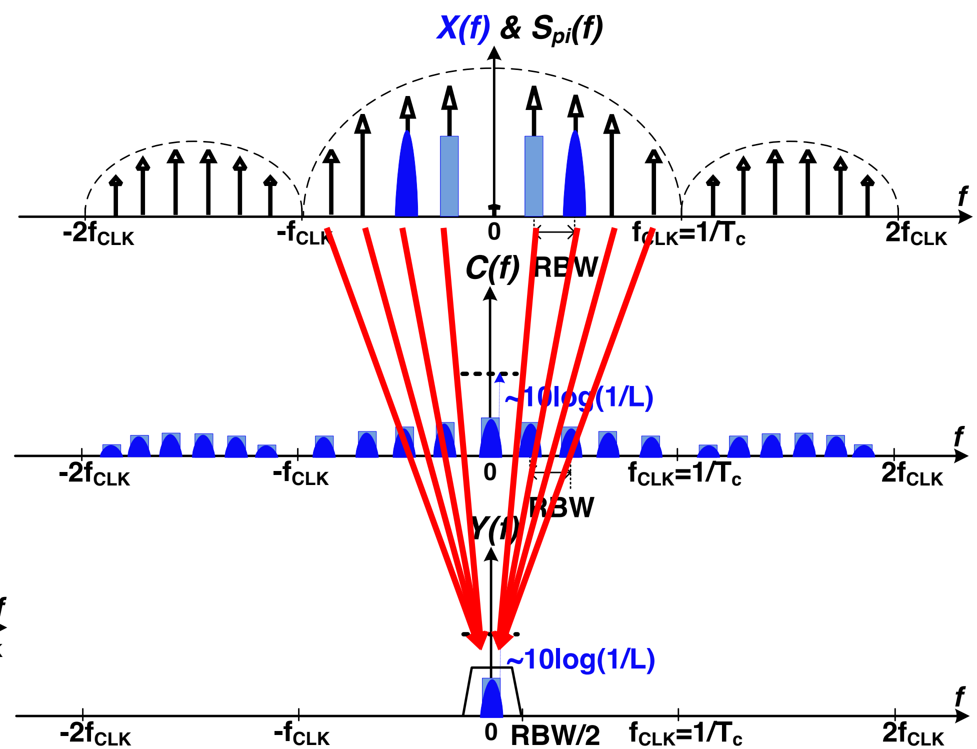
Block diagram of a PN Mixer + LPF



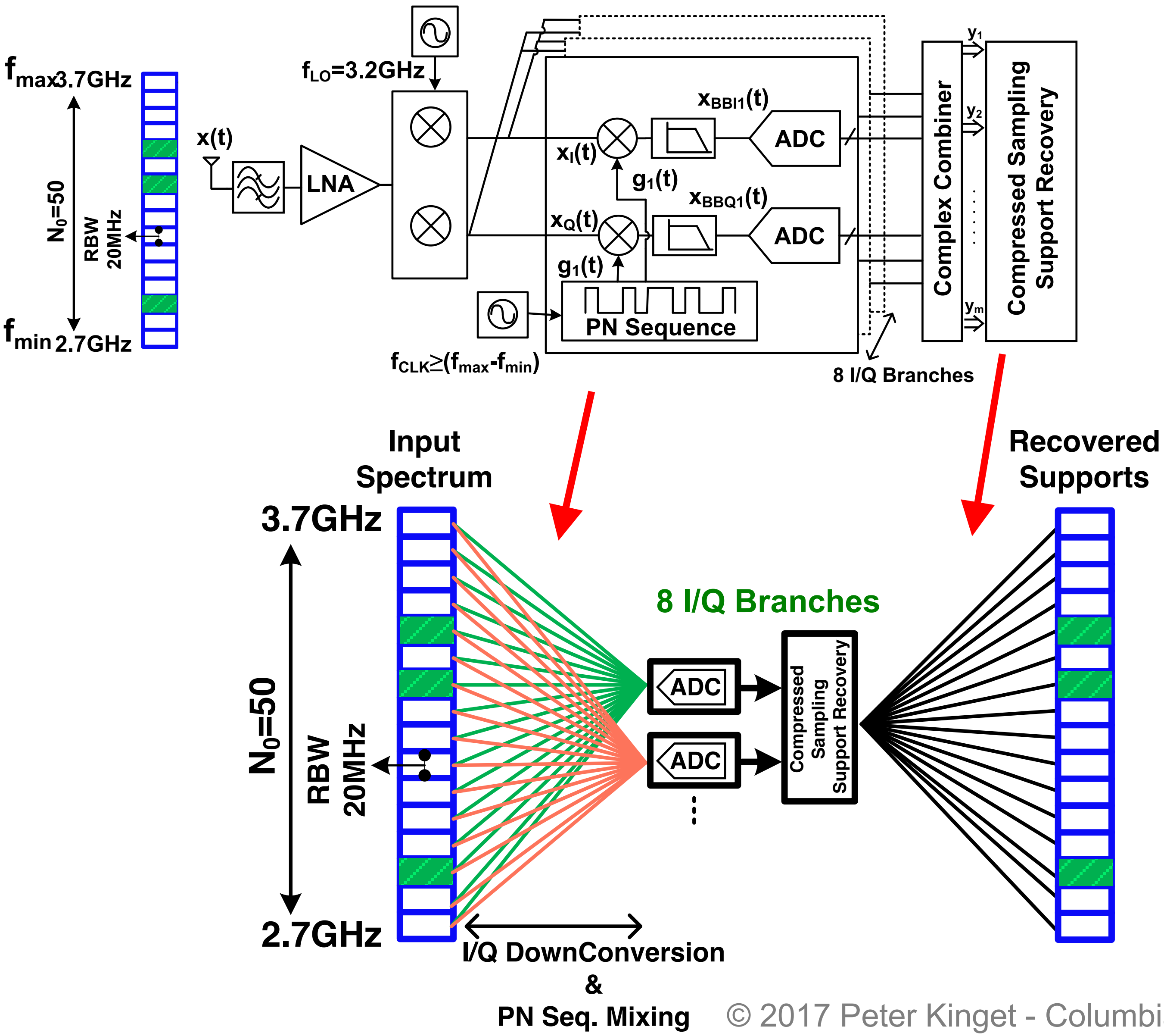
PN Sequence in Time Domain



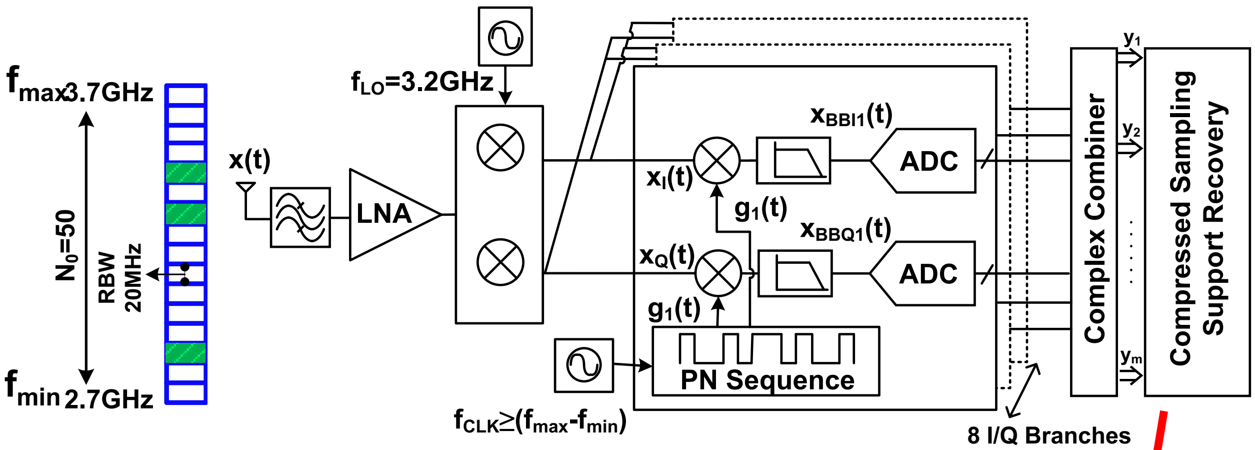
PN Sequence Spectrum

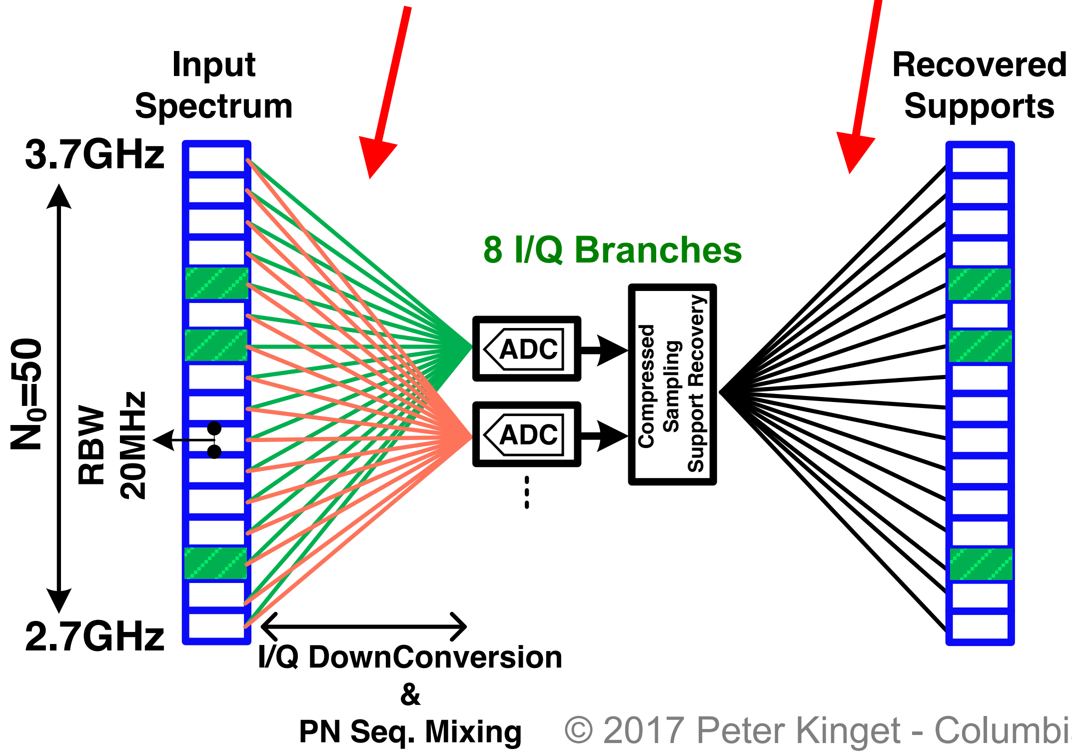


Quadrature Analog-to-Information Converter (QAIC)



Quadrature Analog-to-Information Converter (QAIC)





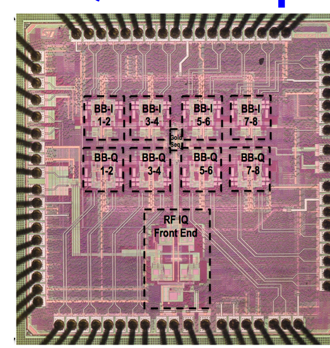
Band-pass CS Approach

PN Sequence
Clock Freq. = 1.26GHz
Length = 63

# of Branches = 8 I/Q

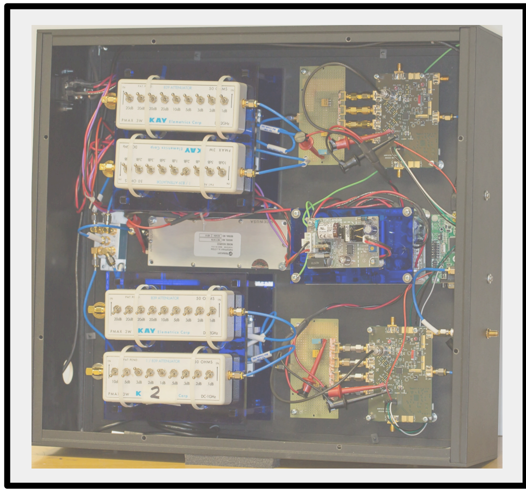
Energy Consumption
Power Cons. = 80mW
Scan Time = 4uSec

QAIC Chip

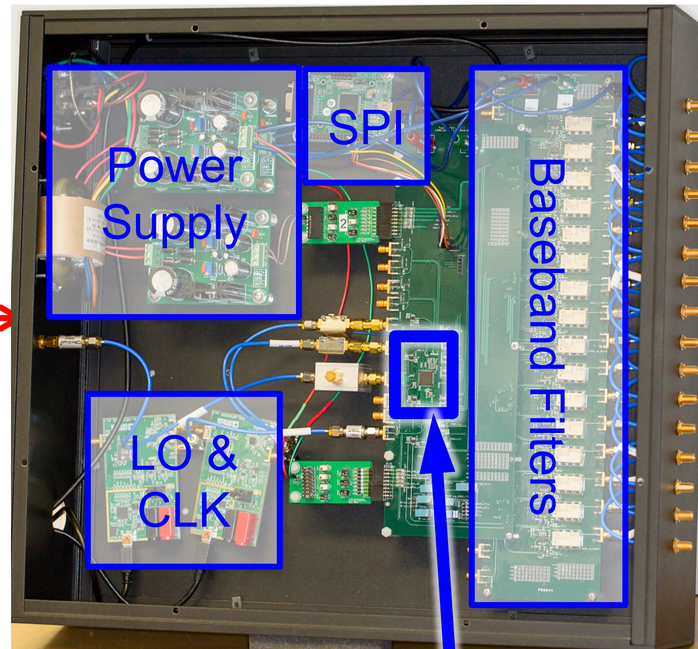


Rapid Interferer Detector Demonstration

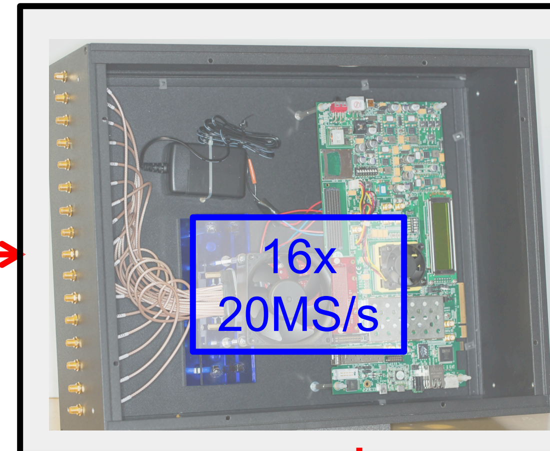
1GHz MULTI-BAND SIGNAL GENERATOR



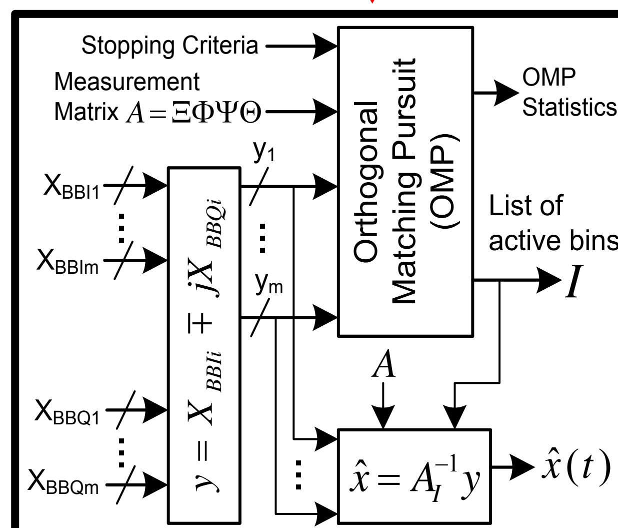
QAIC SYSTEM



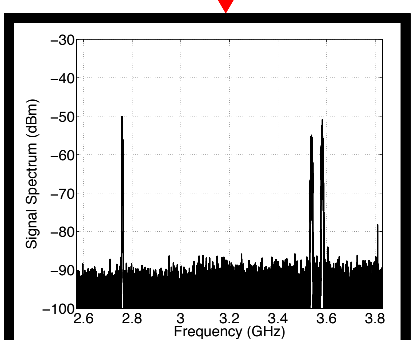
ADC/FPGA SAMPLING SYSTEM



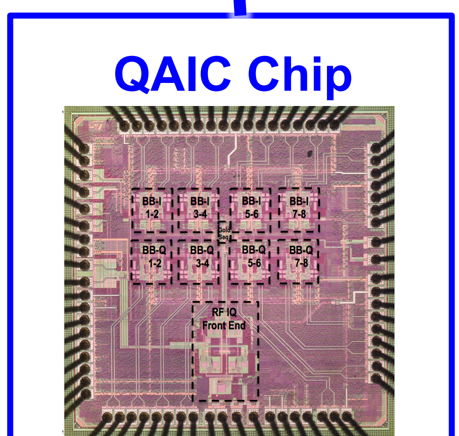
Matlab



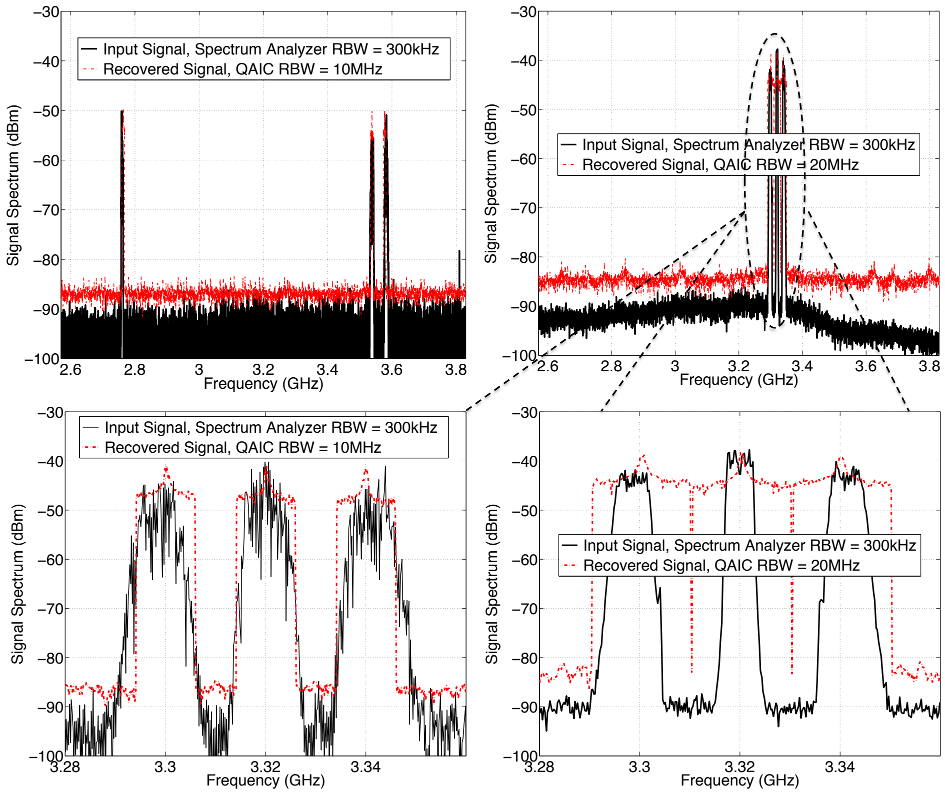
SPECTRUM ANALYZER



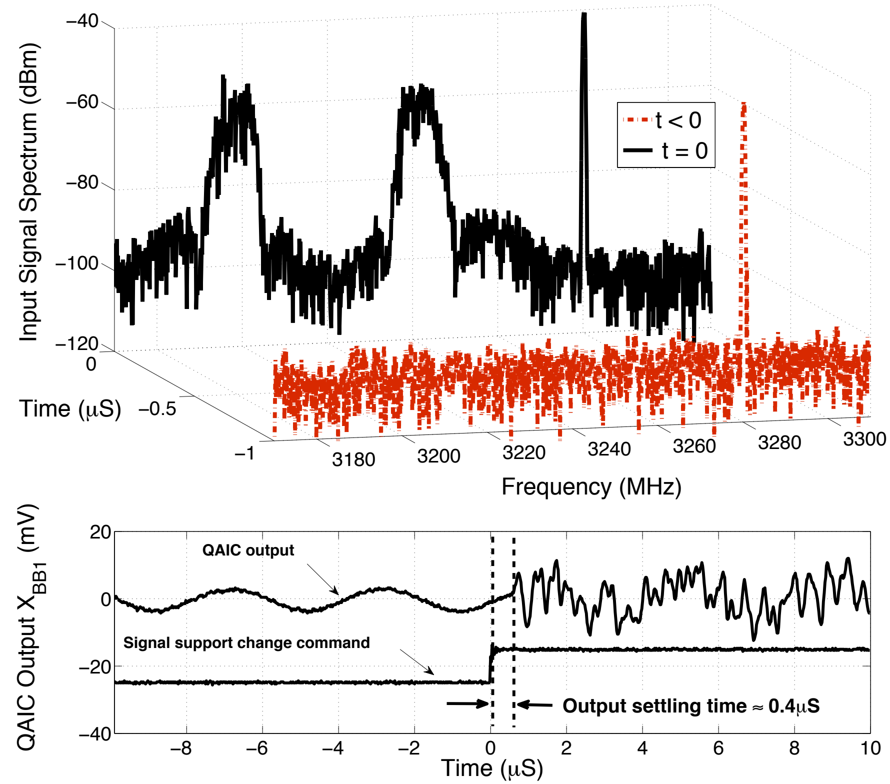
Input Spectrum



Wideband Rapid Interferer Detection with a Compressed Sampling QAIC



Wideband Rapid Interferer Detection
RF Span=1GHz; T=4.4uS



QAIC Detector Time Agility

[Yazicigil]

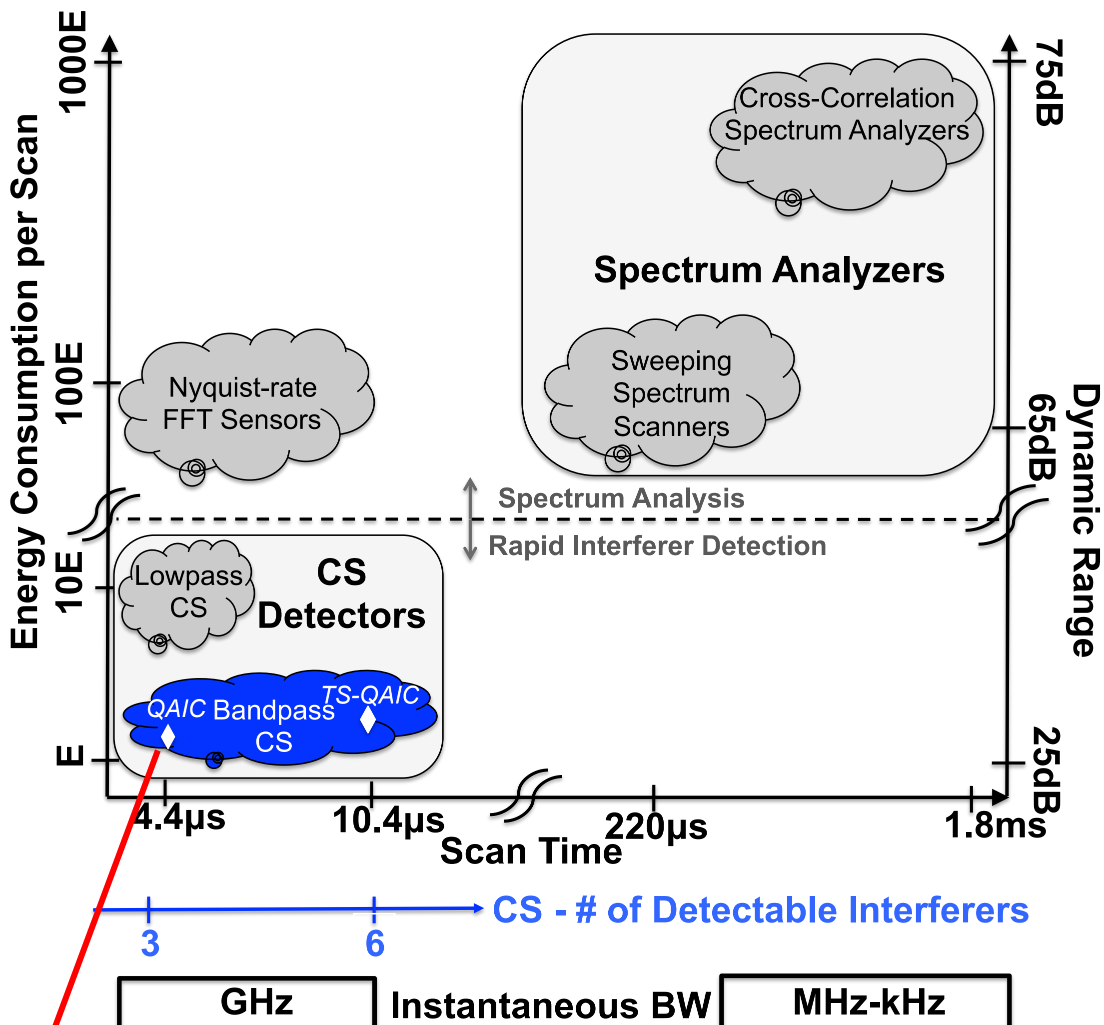
Comparison of Spectrum Scanner/Sensor Architectures

System Attributes	Sweeping Spectrum Scanner	Nyquist FFT Spectrum Sensor	QAIC
Scan Time	220μs	4μs	4.4μs **50x faster**
Energy Consumption	50E	50E	E **50x lower**
Aggregate Sampling Rate	40MS/s	2GS/s	320MS/s **6.3x compression**

RBW=20MHz, 1GHz wideband spectrum ranging from 2.7 to 3.7GHz

E: QAIC Energy Consumption

Spectrum Scanners/ Sensors Performance Plane



Performance Scaled for:
RBW: 20MHz
Span: 1GHz
Range: 2.7-3.7GHz
E: QAIC Energy Cons.

❖ Enabling technology for emerging cognitive radio terminals

Conclusions

- *Device* scaling enables new *circuit* solutions for RF applications
- Advanced *signal processing* concepts enable novel architectures for RF signal processing
- Reconfigurable performance profiles, on-chip DT filtering, and energy-efficient spectrum scanning, will become critical features in cognitive terminals for next generation wireless *systems*

“Crossing the boundaries” enables RF circuit and system innovations

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Tugce Yazicigil

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Yang Xu

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Thank You for Your Attention

Crossing The Boundaries