THE BRAVE NEW WORLD OF WIRELESS COMMUNICATION

Ali M Niknejad & Robert Brodersen

University of California

Berkeley Wireless
Research Center

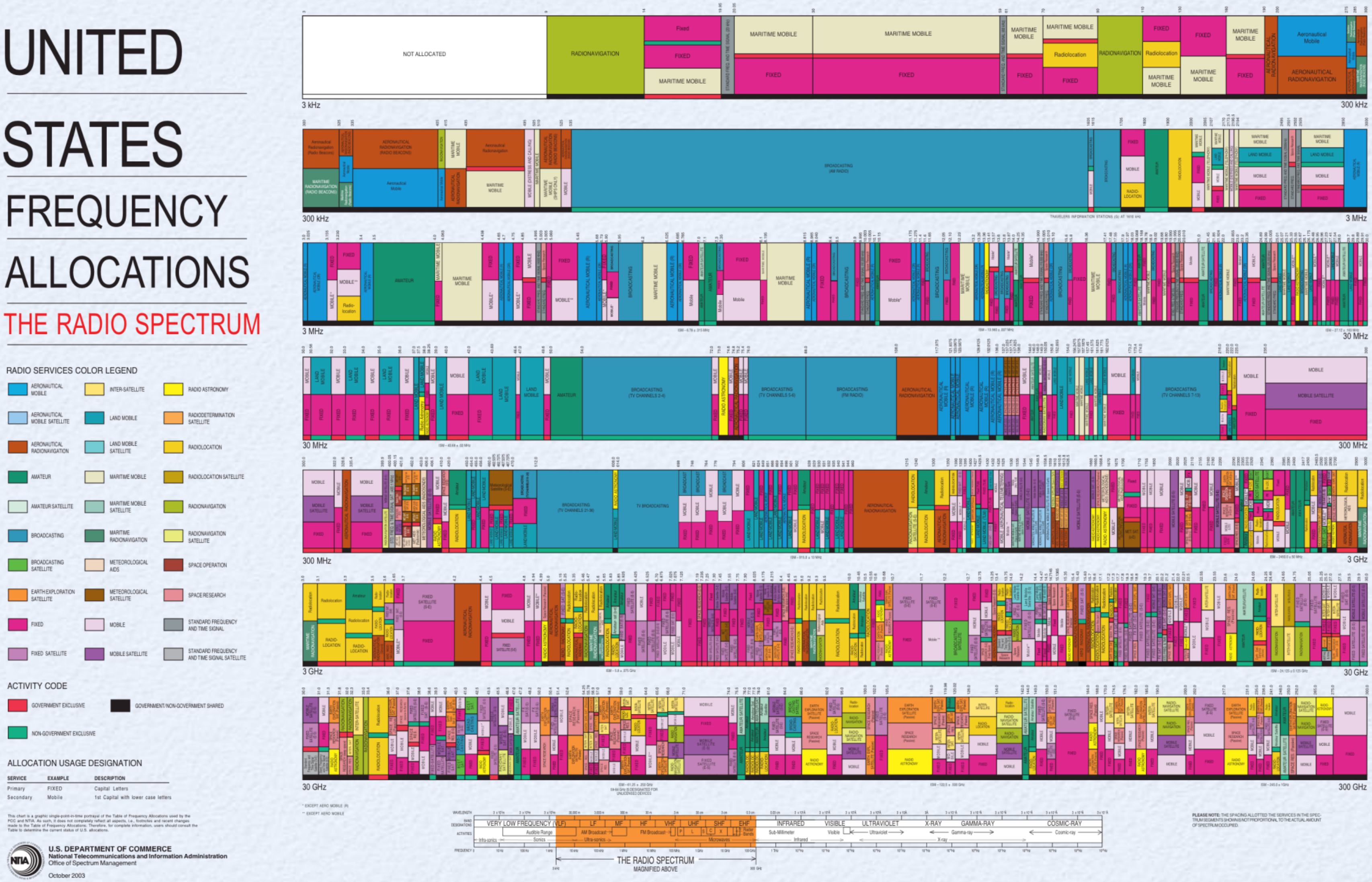
Foundation of Society

- Food, Water, and *Electricity*
- Ethics, Liberty, Equality, Freedom of Speech, Justice
  - (regardless of race, ethnicity, gender, and age)
- Access to Information
  - Telephone, Entertainment, Internet
- Universal wireless connectivity!

Outline

- Searching for spectrum in a seemingly crowded space
- New models for spectrum sharing:
  - Underlay technologies such as UWB
  - Overlay technology such as Cognitive Radio
  - Unused spectrum such as 60 GHz

Spectrum Allocation



UNITED
STATES
FREQUENCY
ALLOCATIONS

THE RADIO SPECTRUM

RADIO SERVICES COLOR LEGEND

- AERONAUTICAL MOBILE
- AERONAUTICAL MOBILE SATELLITE
- AERONAUTICAL RADIONAVIGATION
- AMATEUR
- AMATEUR SATELLITE
- BROADCASTING
- BROADCASTING SATELLITE
- EARTH EXPLORATION SATELLITE
- FIXED
- FIXED SATELLITE
- INTER-SATELLITE
- LAND MOBILE
- LAND MOBILE SATELLITE
- MARITIME MOBILE
- MARITIME MOBILE SATELLITE
- MARITIME RADIONAVIGATION
- METEOROLOGICAL AIDS
- METEOROLOGICAL SATELLITE
- MOBILE
- MOBILE SATELLITE
- RADIO ASTRONOMY
- RADIODETERMINATION SATELLITE
- RADIOLOCATION
- RADIOLOCATION SATELLITE
- RADIONAVIGATION
- RADIONAVIGATION SATELLITE
- SPACE OPERATION
- SPACE RESEARCH
- STANDARD FREQUENCY AND TIME SIGNAL
- STANDARD FREQUENCY AND TIME SIGNAL SATELLITE

ACTIVITY CODE

- GOVERNMENT EXCLUSIVE
- GOVERNMENT/NON-GOVERNMENT SHARED
- NON-GOVERNMENT EXCLUSIVE

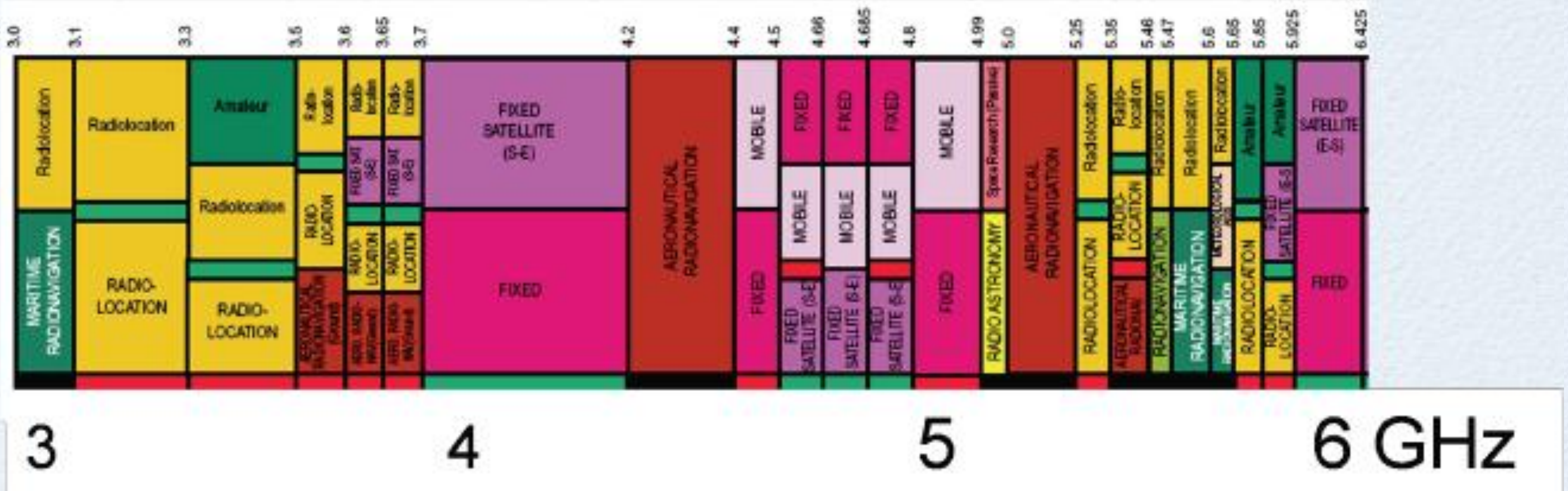
ALLOCATION USAGE DESIGNATION

SERVICE	EXAMPLE	DESCRIPTION
Primary	FIXED	Capital Letters
Secondary	Mobile	1st Capital with lower case letters

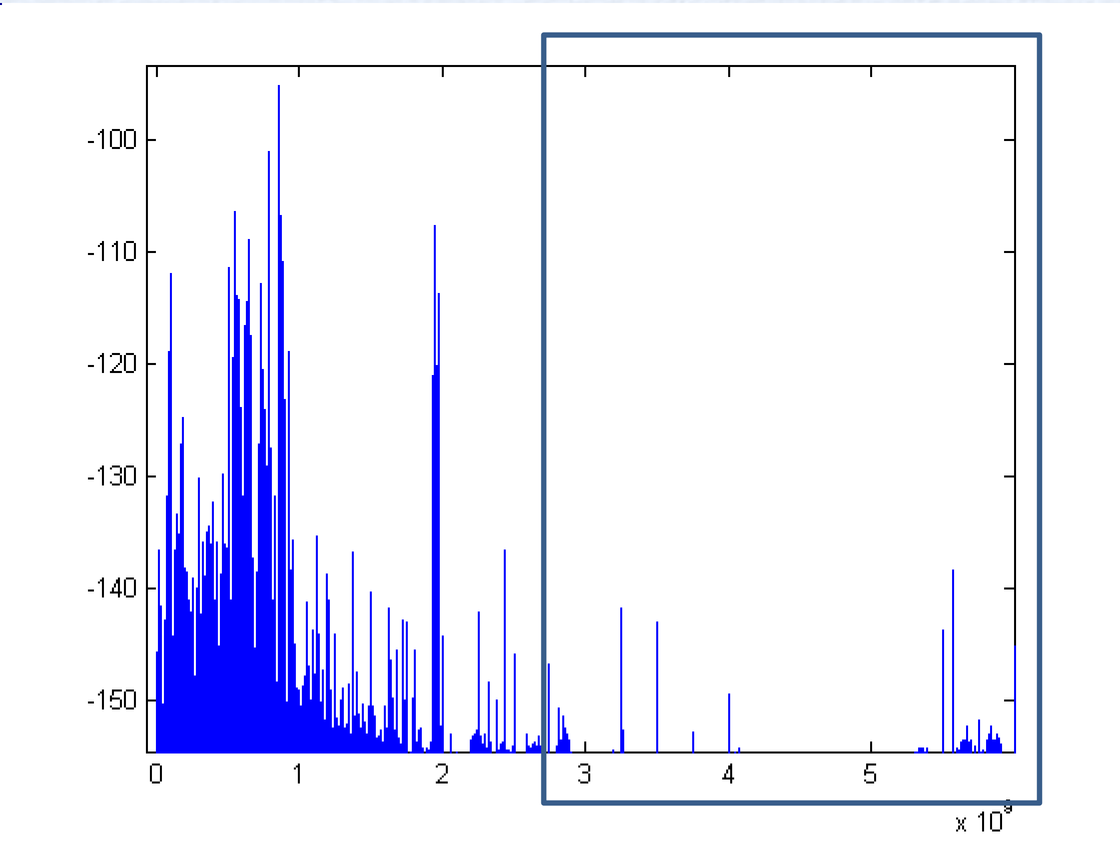
This chart is a graphic single-point-in-time portrayal of the Table of Frequency Allocations used by the FCC and NTIA. As such, it does not completely reflect all aspects, i.e., footnotes and recent changes made to the Table of Frequency Allocations. Therefore, for complete information, users should consult the Table to determine the current status of U.S. allocations.

U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management
October 2003

3-10 Ghz is crowded?

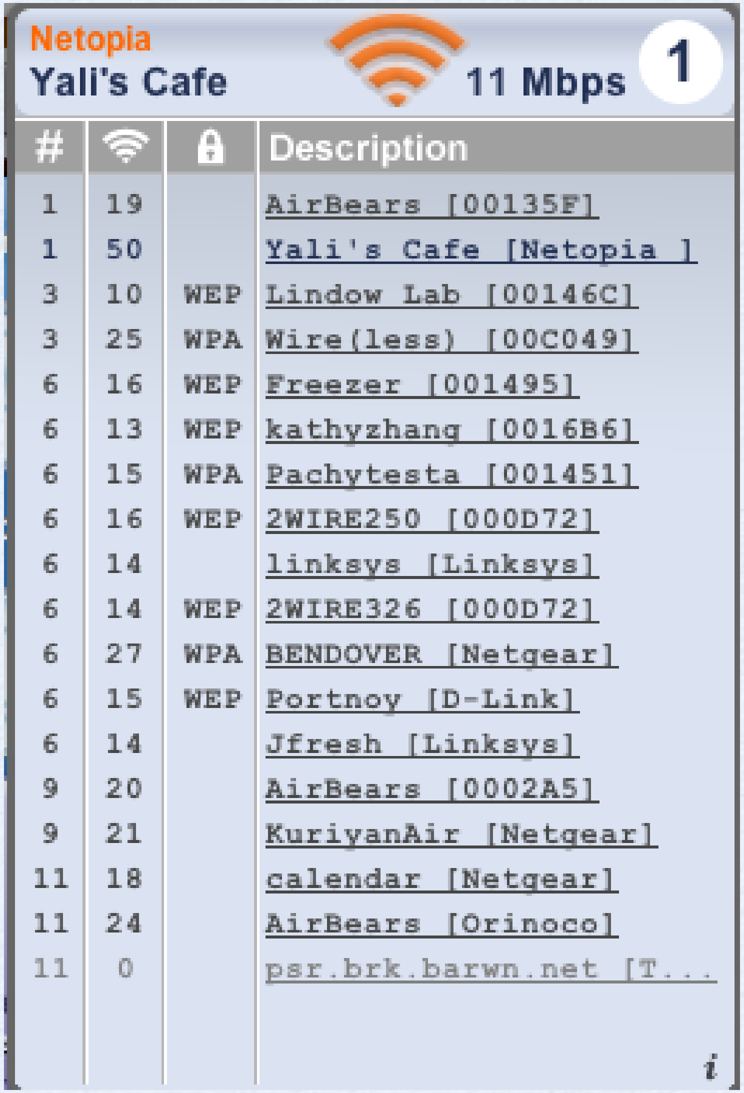


Spectrum Reality



- Measurements performed in downtown Berkeley (BWRC)
- 3-6 GHz poorly utilized

2.4 GHz Band



Netopia
Yali's Cafe
11 Mbps
1

#	📶	🔒	Description
1	19		AirBears [00135F]
1	50		Yali's Cafe [Netopia]
3	10	WEP	Lindow Lab [00146C]
3	25	WPA	Wire(less) [00C049]
6	16	WEP	Freezer [001495]
6	13	WEP	kathyzhang [0016B6]
6	15	WPA	Pachytesta [001451]
6	16	WEP	2WIRE250 [000D72]
6	14		linksys [Linksys]
6	14	WEP	2WIRE326 [000D72]
6	27	WPA	BENDOVER [Netgear]
6	15	WEP	Portnoy [D-Link]
6	14		Jfresh [Linksys]
9	20		AirBears [0002A5]
9	21		KuriyanAir [Netgear]
11	18		calendar [Netgear]
11	24		AirBears [Orinoco]
11	0		psr.brk.barwn.net [T...

← university

← café signal

} apartments…

← university

Cognitive Radio

- Assign primary users to spectrum
- Allow non-primary users to utilize spectrum if they can detect non usage
- If primary users needs spectrum, move to a new frequency band

Backyard Question

- If someone walks through your backyard while you’re on vacation, do you mind?
- By the way, there’s no way you’ll ever know this happened. Are you still worried about it?

Café Analogy

- At a restaurant, seats are assigned.
- Where do you sit at a café?

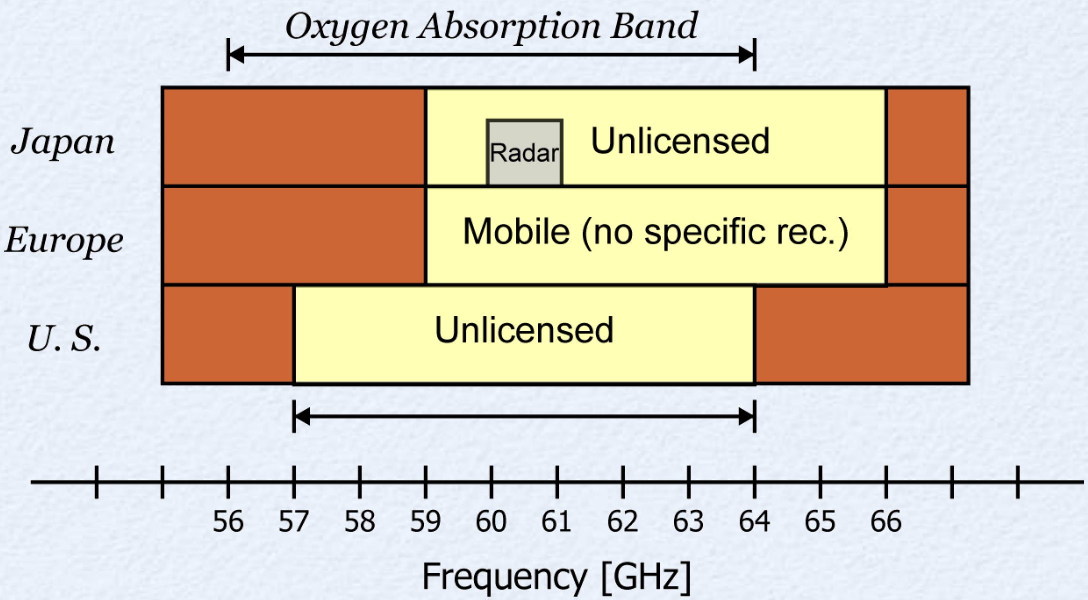
Cafe Seating Policy

- If you arrive in an empty cafe, you take the first seat. Probably the best seat ...
- After the last table (next to kitchen or *worse*) is occupied, where do you go?
- Why not share a table? Which table do you share? The biggest and "prettiest" one ...
- But why not sit at those "reserved" tables?

UWB (Sit Under the Table)

- Build a radio that utilizes existing spectrum without interference to “primary” users
- Transmit power below EMI mask of -41.3 dBm/MHz (bury yourself in noise)
- Utilize coding and large bandwidth to transmit information
- They can’t see you , but you can see them!
  - “Radar”

Big Tables at 60 Ghz



- But there’s lots of bandwidth to be had! 7 GHz of unlicensed bandwidth in the U.S. and Japan
- Same amount of bandwidth is available in the 3-10 UWB band, TX power level is 10^4 times higher!

New Paradigms

- Underlay: Restrict transmit power and operate over ultra wide bandwidths (UWB)
- Far away: Operate in currently unused frequency bands (60 GHz)
- Overlay: Share spectrum with primary users

Comparison

	UWB	60 GHz	CR
Spectrum Access	Underlay	Unlicensed	Overlay
Carrier	[0-1],[3-10] GHz	[57-64] GHz	[0- ∞] GHz
Bandwidth	> 500 MHz	> 1 GHz	> 1 GHz
Data Rates	~ 100 Mb/s	~ 1 Gb/s	~ 10-1000 Mb/s
Spectral Efficiency	~0.2-1 b/s/Hz	~ 1 b/s/Hz	~ 0.1-10 b/s/Hz
Range	1-10 m	1-10 m	1m – 10 km

Under the Table

UWB

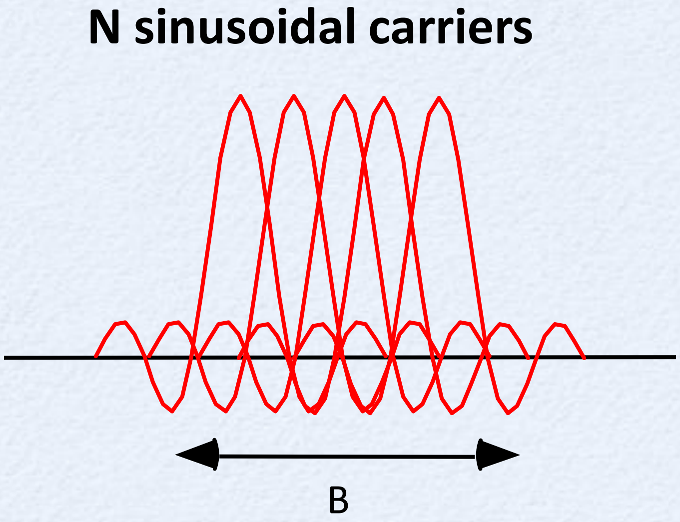
UWB

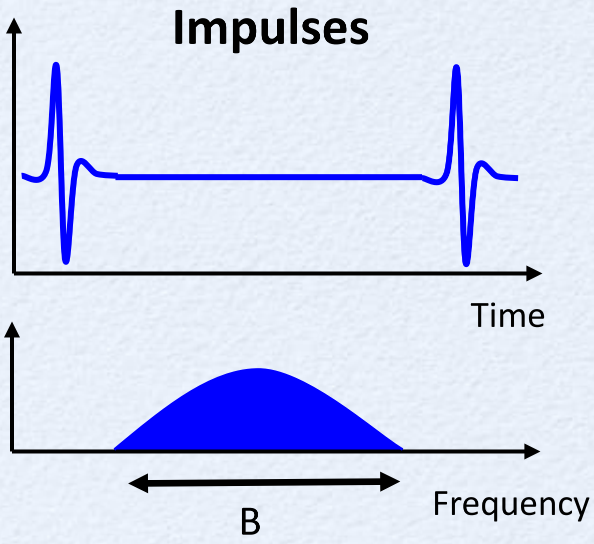
According to the FCC:

> *“Ultrawideband radio systems typically employ pulse modulation where extremely narrow (short) bursts of RF energy are modulated and emitted to convey information. … the emission bandwidths … often exceed one gigahertz. In some cases “impulse” transmitters are employed where the pulses do not modulate a carrier.”*

Federal Communications Commission,
ET Docket 98-153, First Report and Order, Feb. 2002

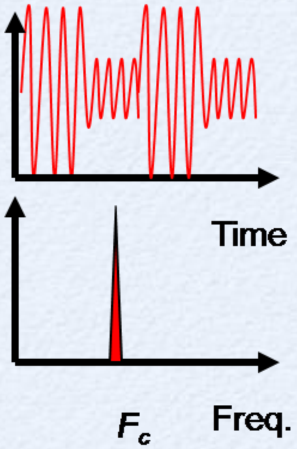
OFDM or Pulses?


N sinusoidal carriers

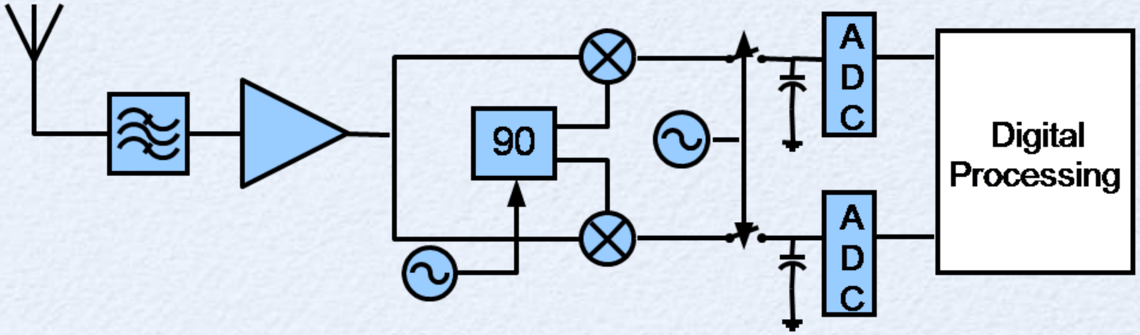

Impulses

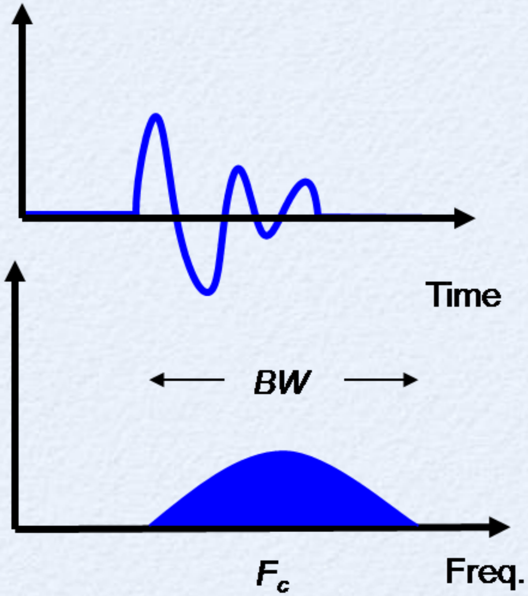
- Well known sinusoidal approach based on OFDM
- New approach based on short pulse transmission
- Unknown ultimate performance and implementation advantages (or disadvantages)
- New applications – e.g. locationing and imaging

More “Digital” Radios

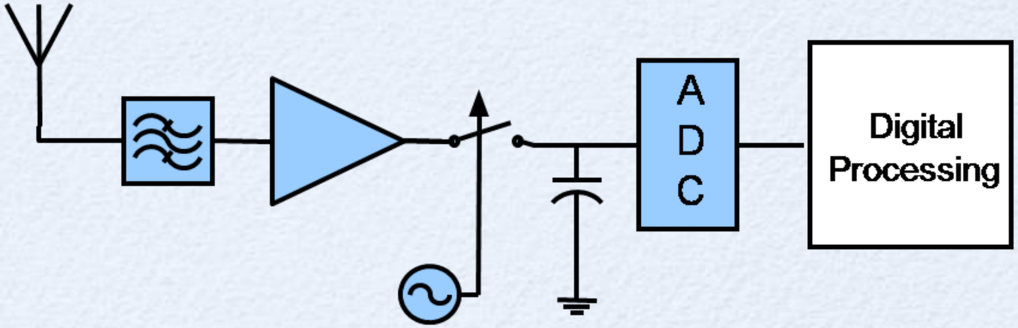


Sinusoidal Downconversion Radio



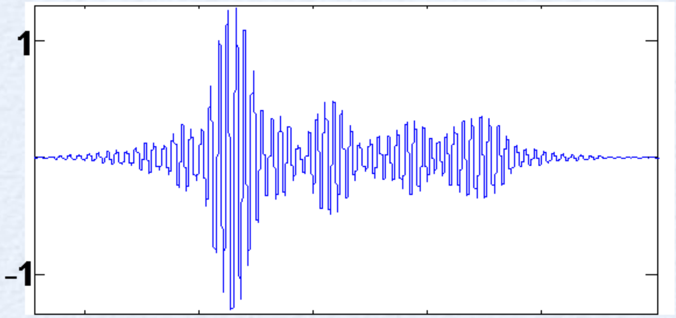


Subsampling Impulse Radio

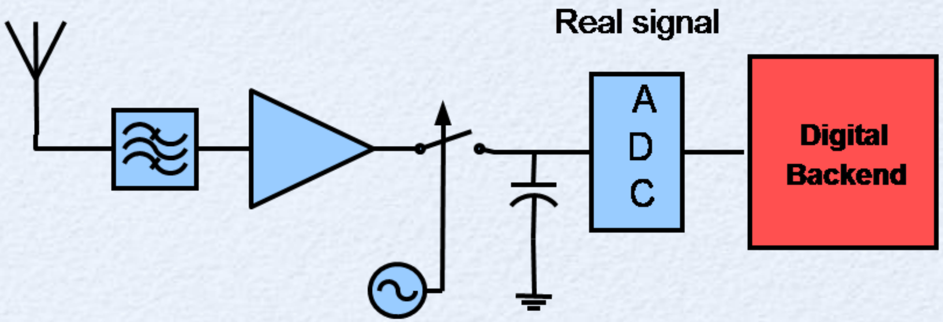


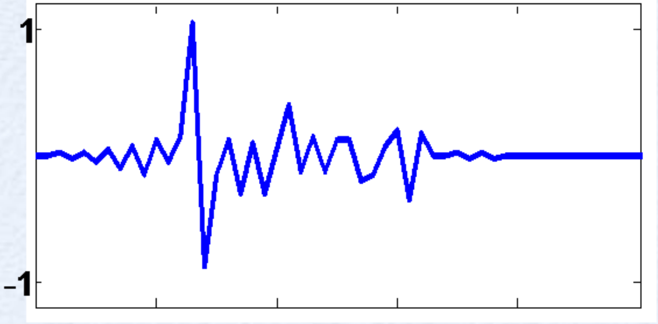
Lower complexity, less power

Sampling Short Pulses

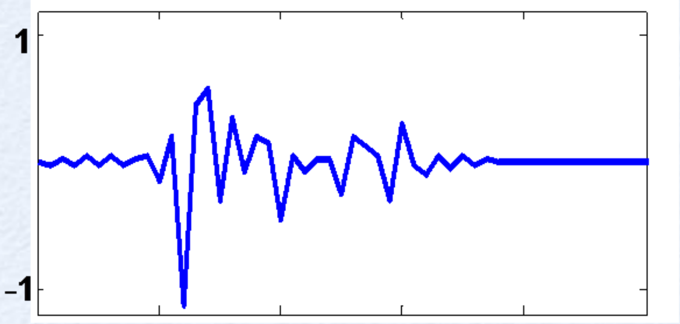


Received signal (3-4 GHz)





Sampling offset 0 Ts

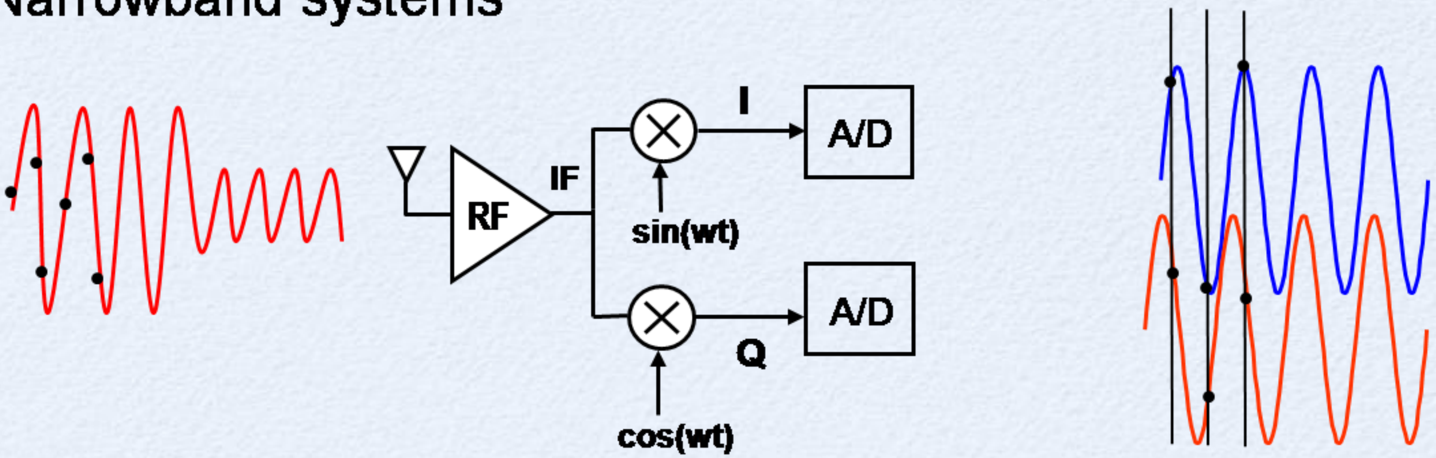


Sampling offset 0.75 Ts

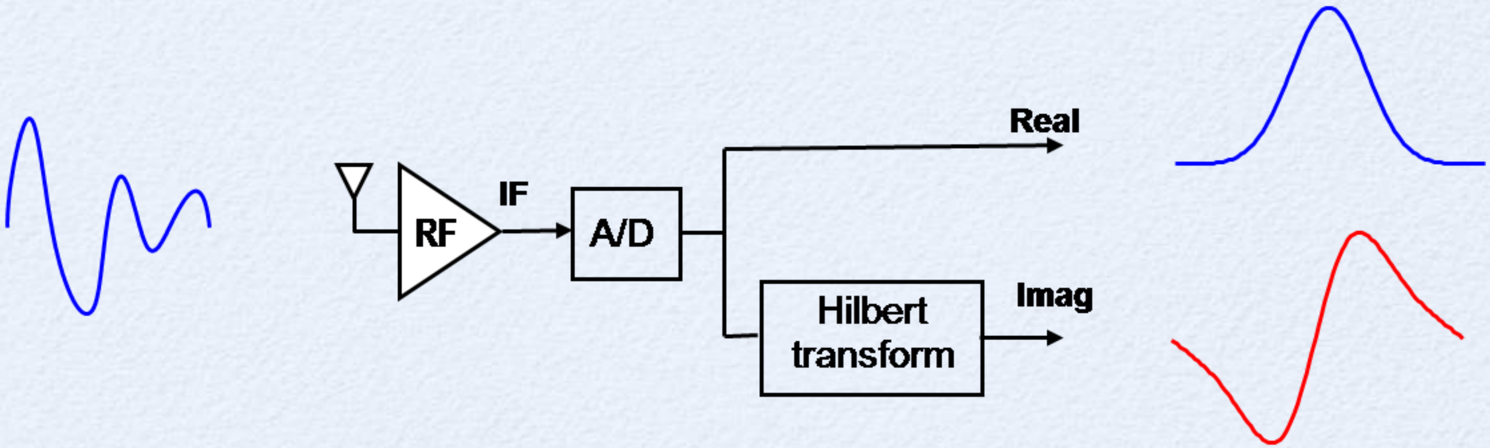
Requires very high sample rates and thus susceptible to small timing offsets

Wideband Quadrature

Narrowband systems



Wideband systems



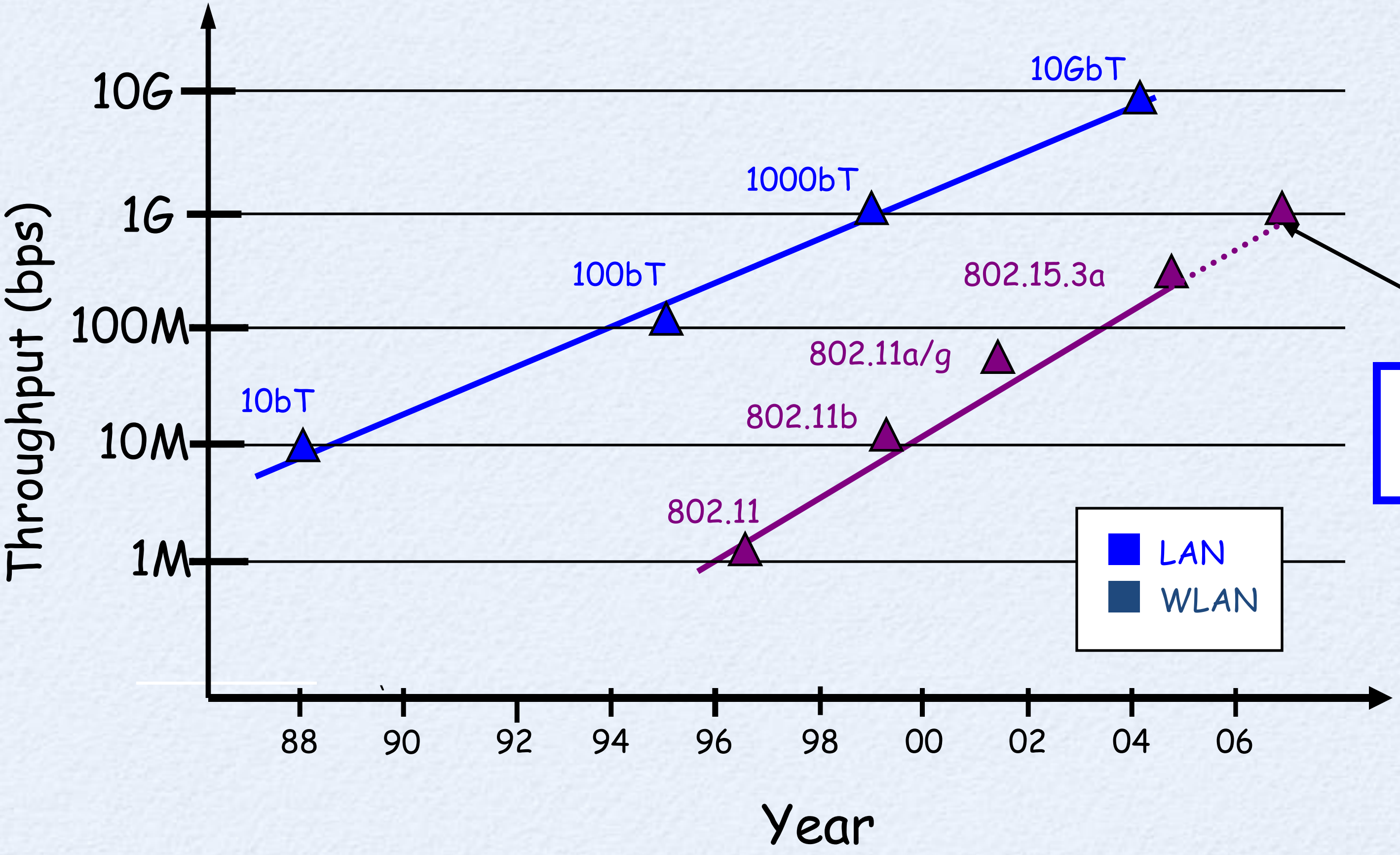
UWB Summary

- Fundamentally a new approach for data transmission
- Use digital processing to reducing dependence on sampling timing offsets with only one A/D
- Simple architecture – “mostly digital”
- Possibility of other new advantages and applications (ranging and imaging)

Big Free Table

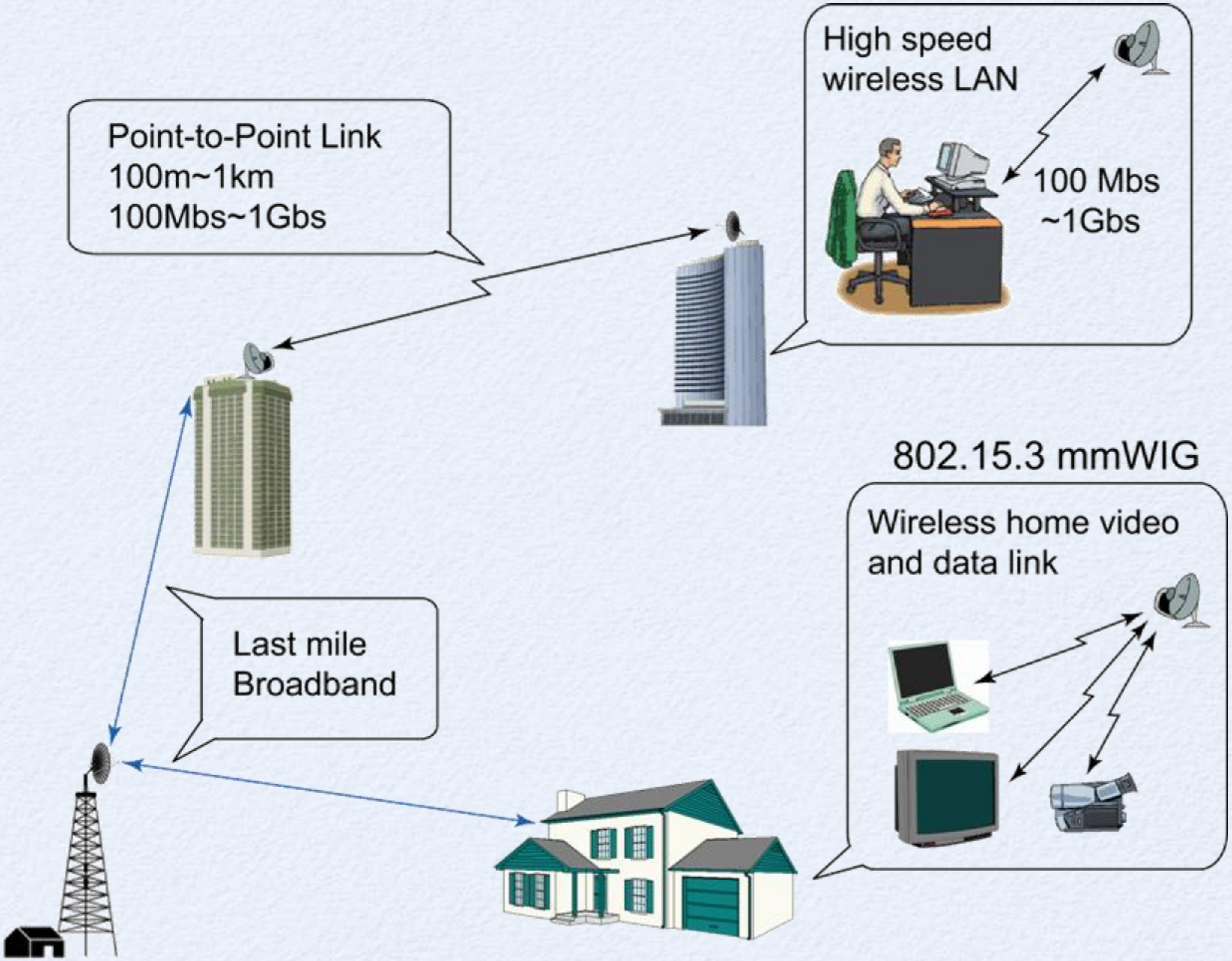
60 GHZ

Thirst for Bandwidth



1Gbps: The next wireless challenge!

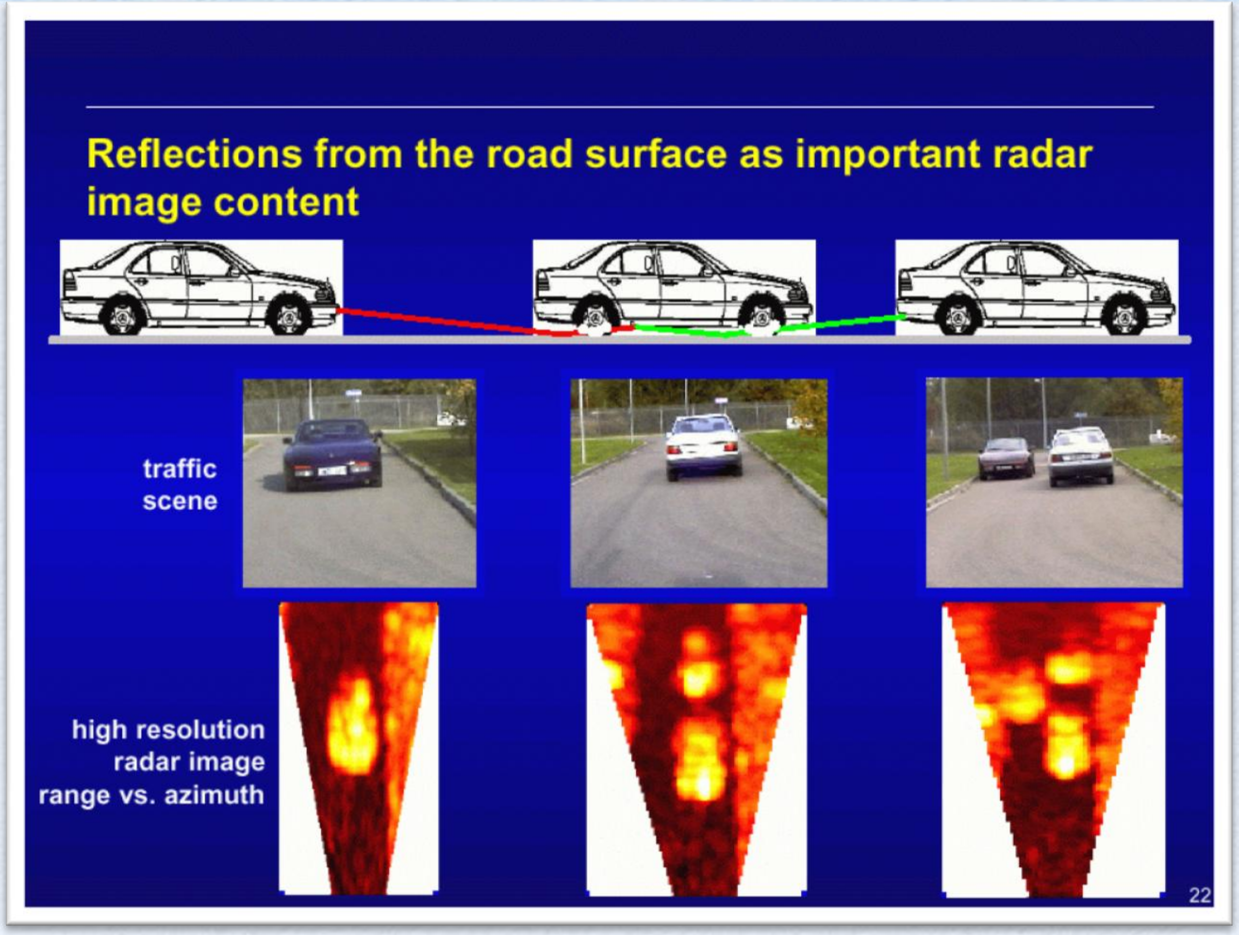
Last inch, Last mile



Extension of Portable

- Extended display for device
  - PDA
  - Digital camera
  - Video camera
- Wireless USB
  - Storage
  - Printer
- Data transfer
  - Digital Camera
  - Video Camera
  - Sync
  - Music
  - Movies

Automotive Radar



Reflections from the road surface as important radar image content

Source: DC, Workshop IMS2002

- Safety, improved functionality, automatic cruise control …

Fear of 60 GHz

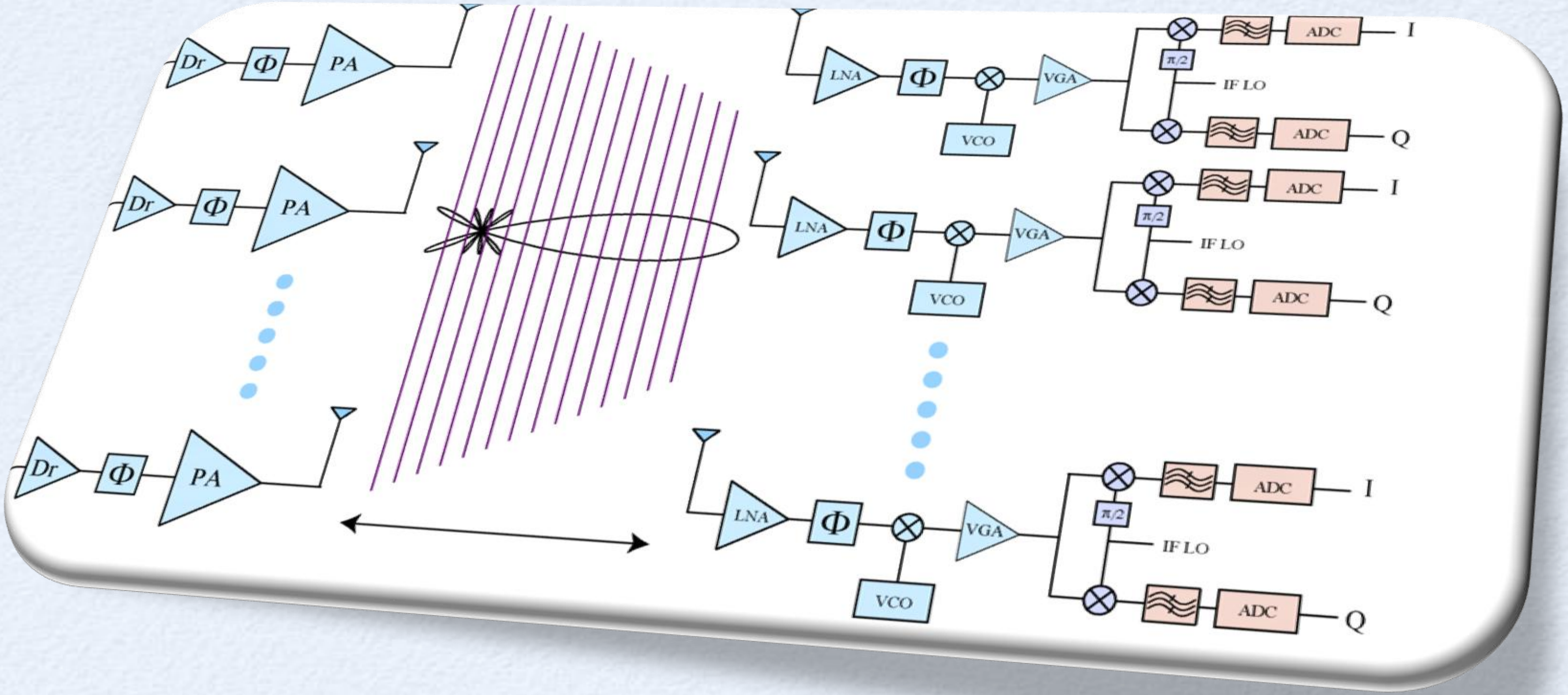
- Does the lumped circuit approximation even hold?
- How do you model the FET?
- Won’t the circuit just radiate way like crazy?
- Substrate losses will be a killer !
- I’m having trouble with 5 GHz models … how do you expect to design at 10 times this frequency?
- Noise goes up with frequency … can’t do a low noise system.
- Signal propagation is really bad.
- Materials are lossy at this frequency.
- …

Can we do it in Si? CMOS?

- High path loss at 60 GHz (relative to 5 GHz) → high gain
- Silicon substrate is lossy → low Q
- CMOS building blocks at 60 GHz
- Design methodology for CMOS *mm*-wave

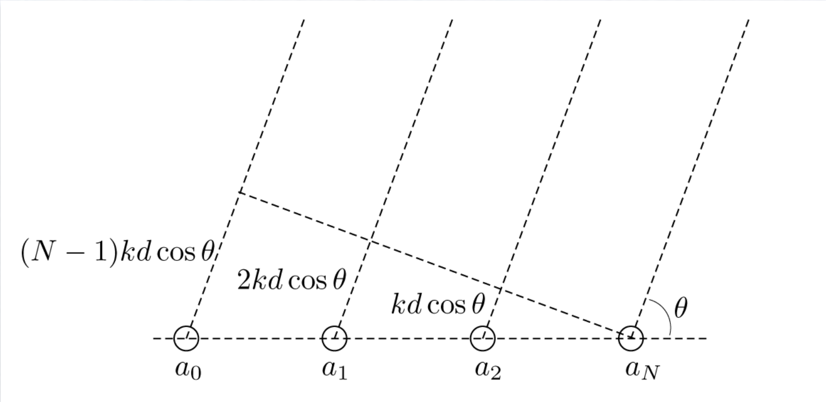
- CMOS is inexpensive and shrinking → higher speeds
- Antenna elements are small → integration into package (multiple transceivers on a single chip)
- Beam forming → improve antenna gain, spatial diversity (resilience to multi-path fading)
- Spatial power combining → PAs easier

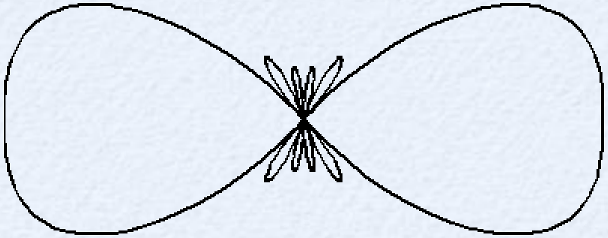
Our Vision



- A fully-integrated low-cost Gb/s data communication using 60 GHz band.
- 10 element array with 10 dB gain implies that a 10 mW PA → 1W isotropic radiator

Antenna Array Properties





- Antenna array is dynamic and can point in any direction
- Enhanced receiver/transmitter antenna gain (reduced PA power, LNA NF)
- Improved diversity
- Reduced multi-path fading
- Null interfering signals
- Capacity enhancement through spatial coding

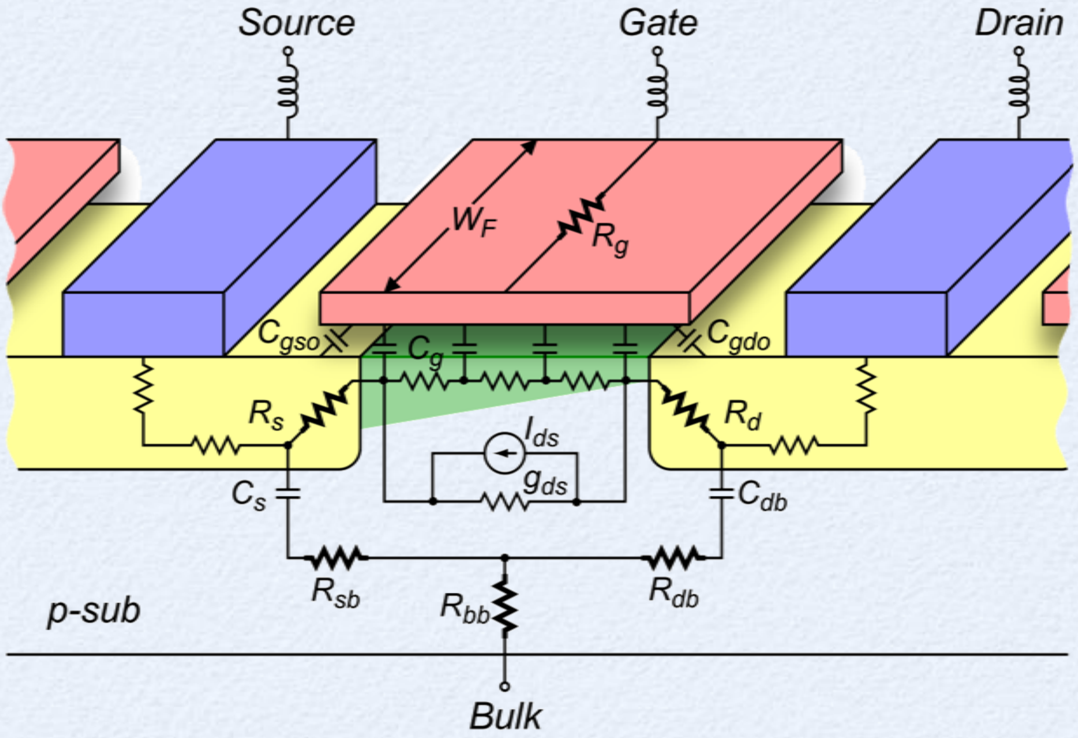
$$f(\theta) = a_0 e^{j(N-1)\overbrace{kd\cos\theta}^{\Psi}} + a_1 e^{j(N-2)\Psi} + \cdots + a_N$$

Modeling at 60 GHz

- Transistors
  - Compact model not verified near f_{max}/f_t
  - Table-based model lacks flexibility
  - Parasitics no longer negligible
  - Highly layout dependent
- Passives
  - Need accurate reactances
  - Loss not negligible
  - Scalable models desired
  - Allows comparison of arbitrary structures

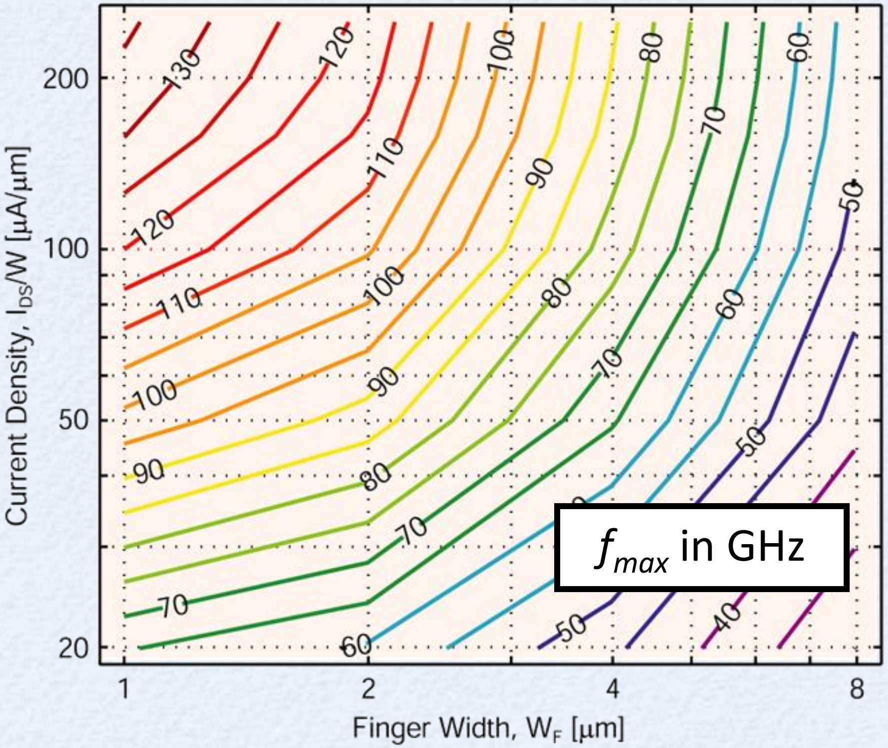
Accurate models required for circuits operating near limit of process

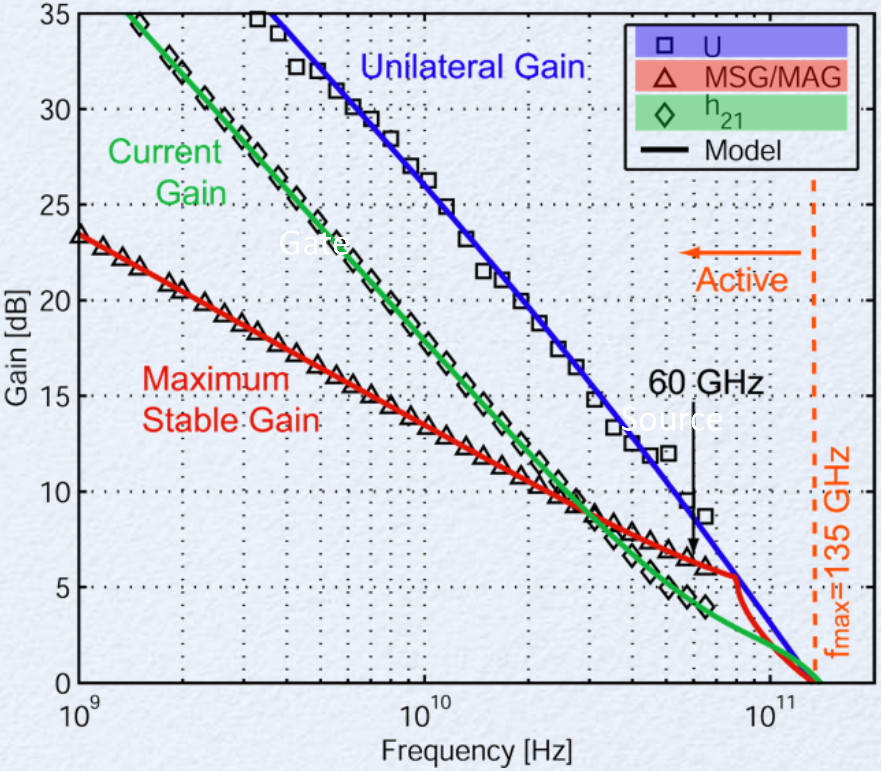
CMOS Modeling Issues



- Active device performance highly layout dependent

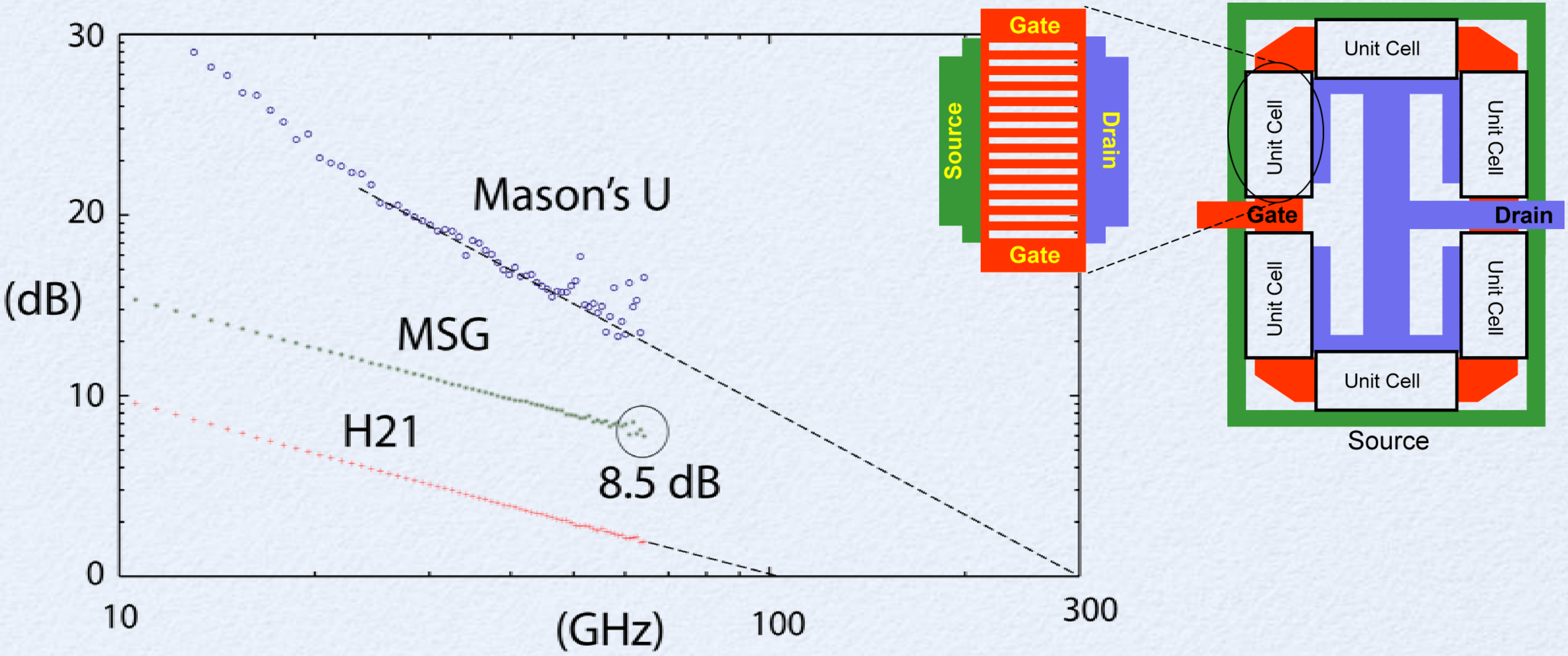
Maximum Available Gain





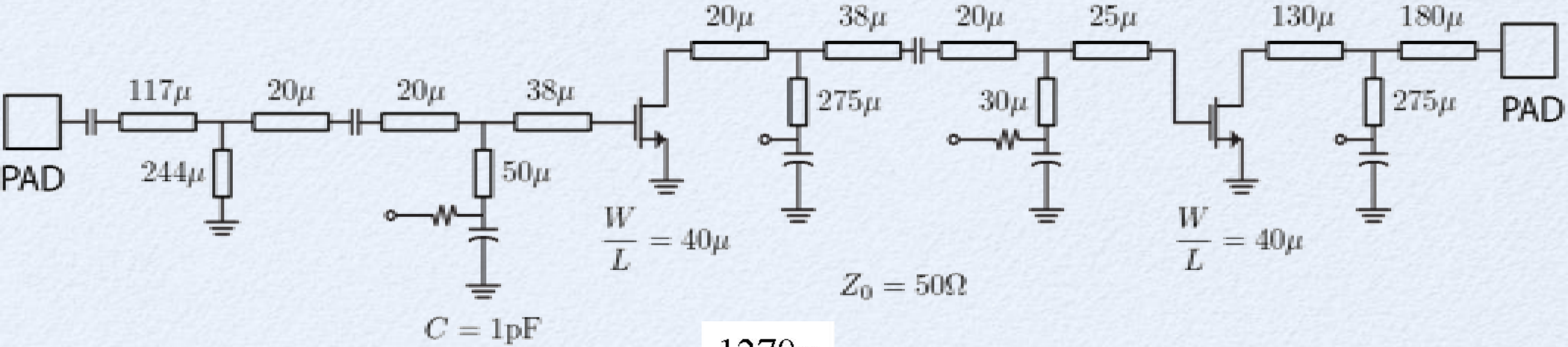
- 60 GHz barely in the money at 130nm.

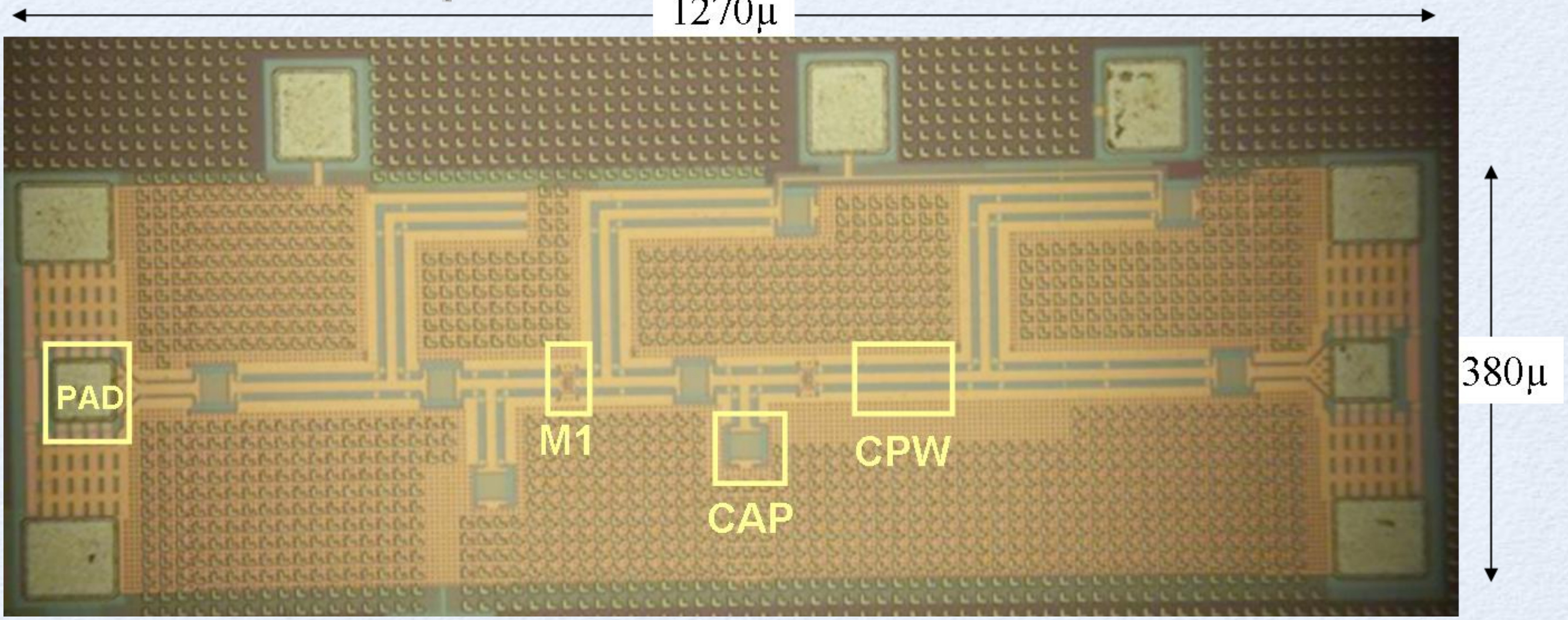
Moore's Law



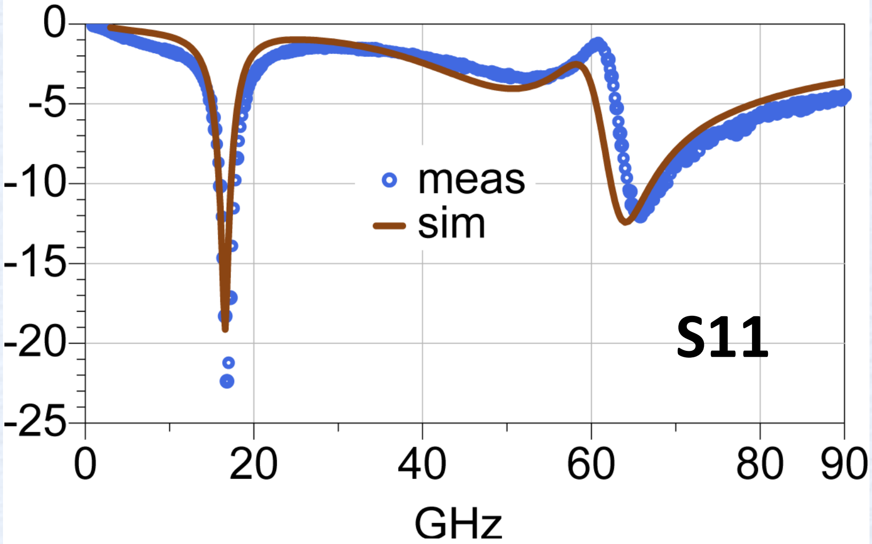
- 90nm CMOS custom layout
- Fmax=300 GHz (extrapolated), Fmax/Ft=3

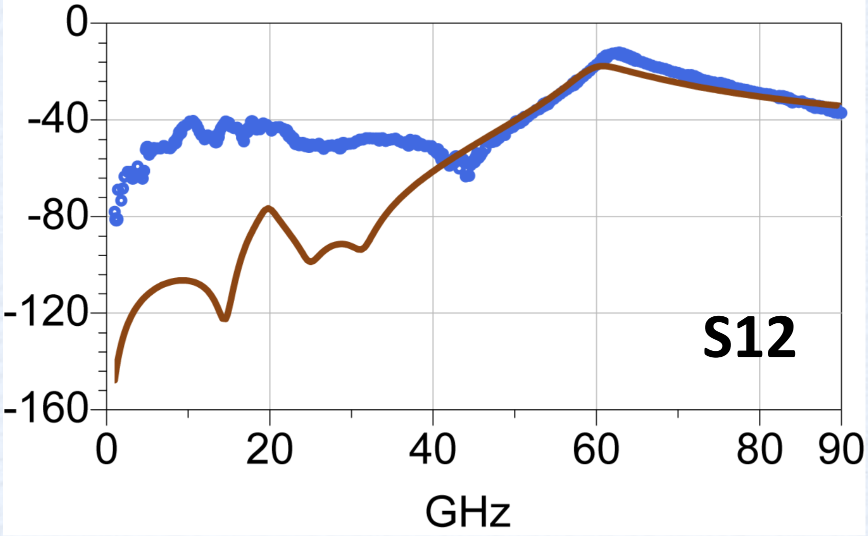
60 GHz LNA

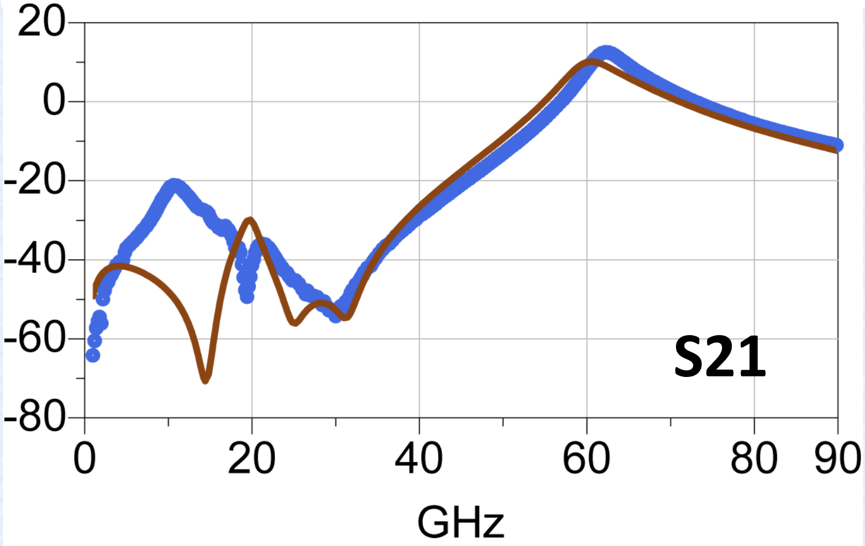

PAD
117μ
20μ
244μ
20μ
38μ
50μ
C = 1pF
W/L = 40μ
20μ
38μ
275μ
20μ
25μ
30μ
Z0 = 50Ω
W/L = 40μ
130μ
180μ
275μ
PAD

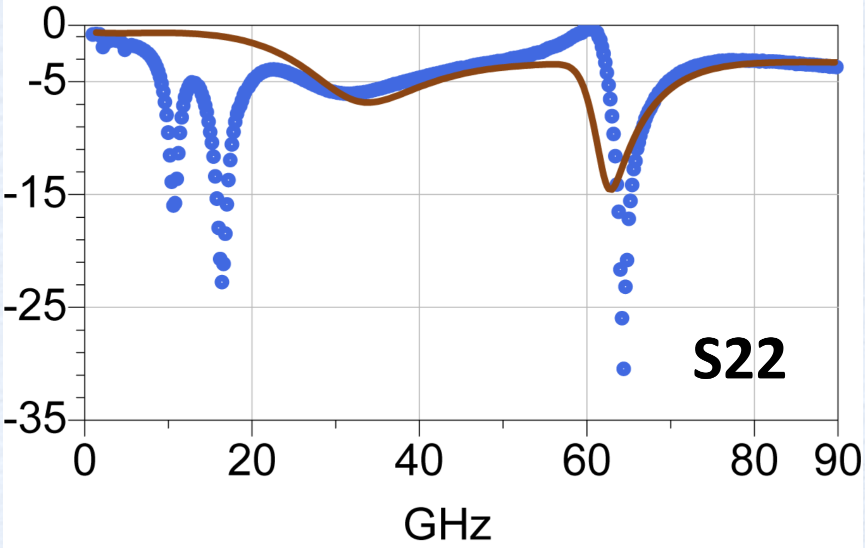

1270μ
380μ
PAD
M1
CAP
CPW

S-Parameter Sim/Measurements

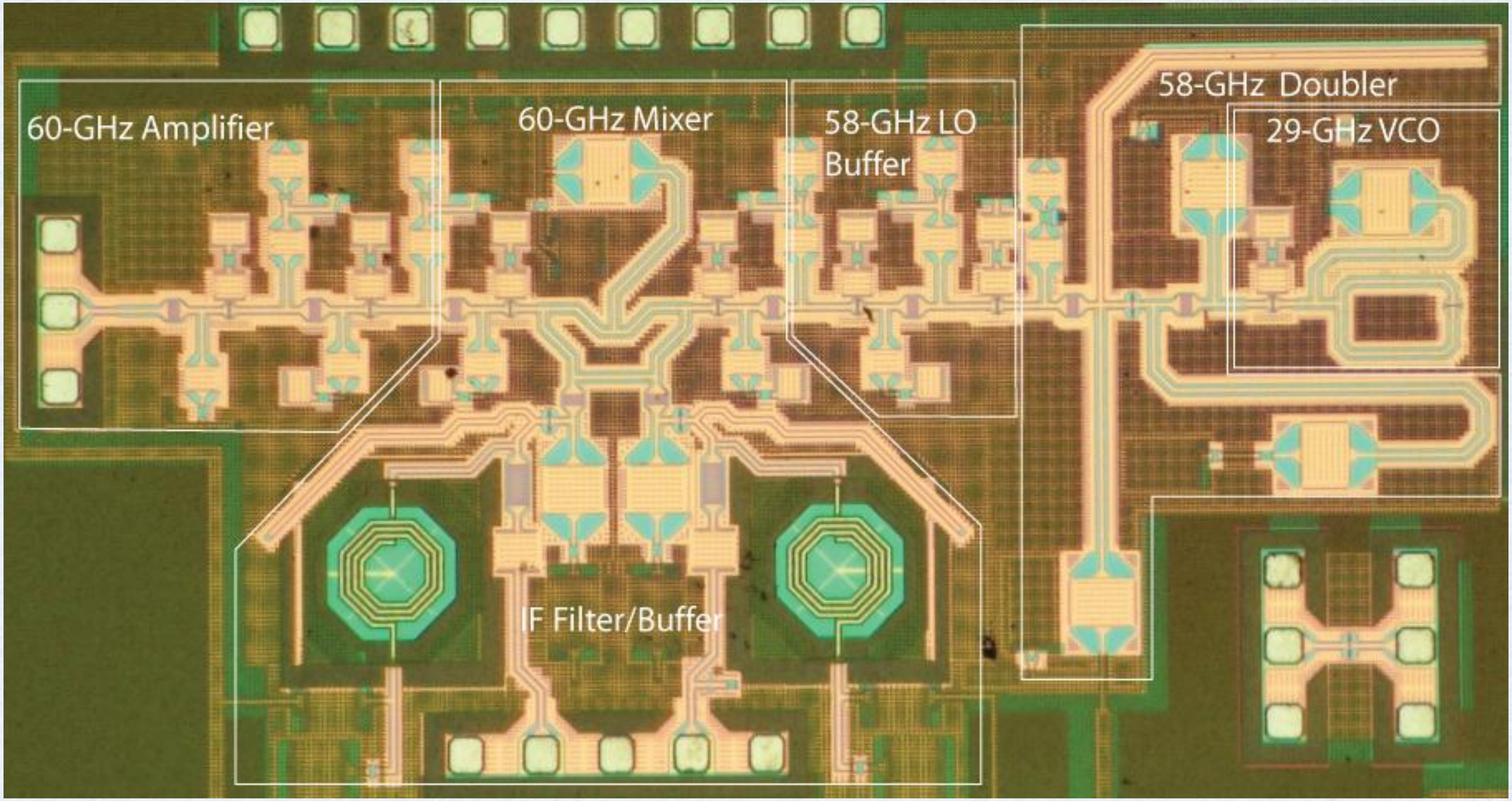






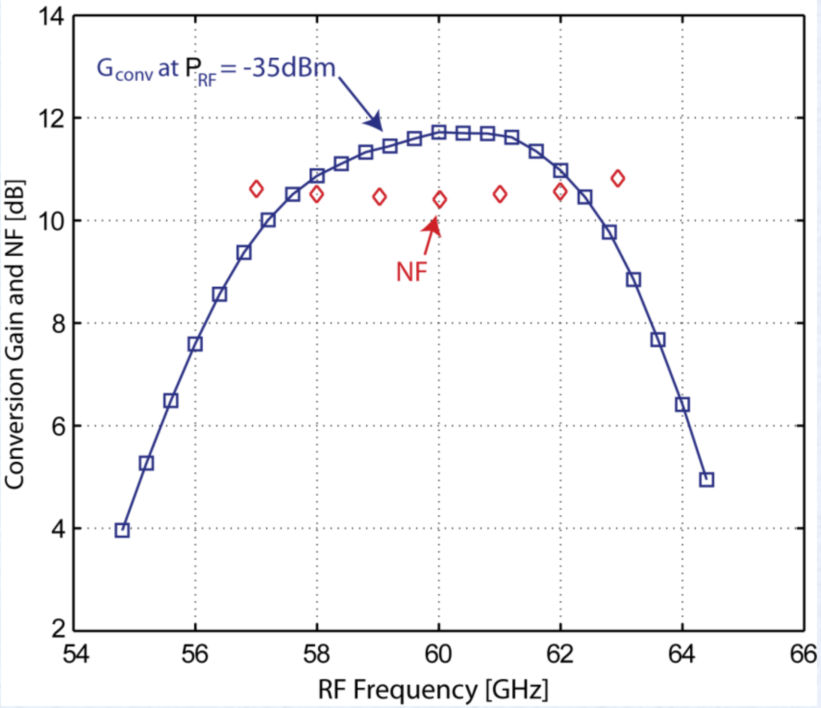


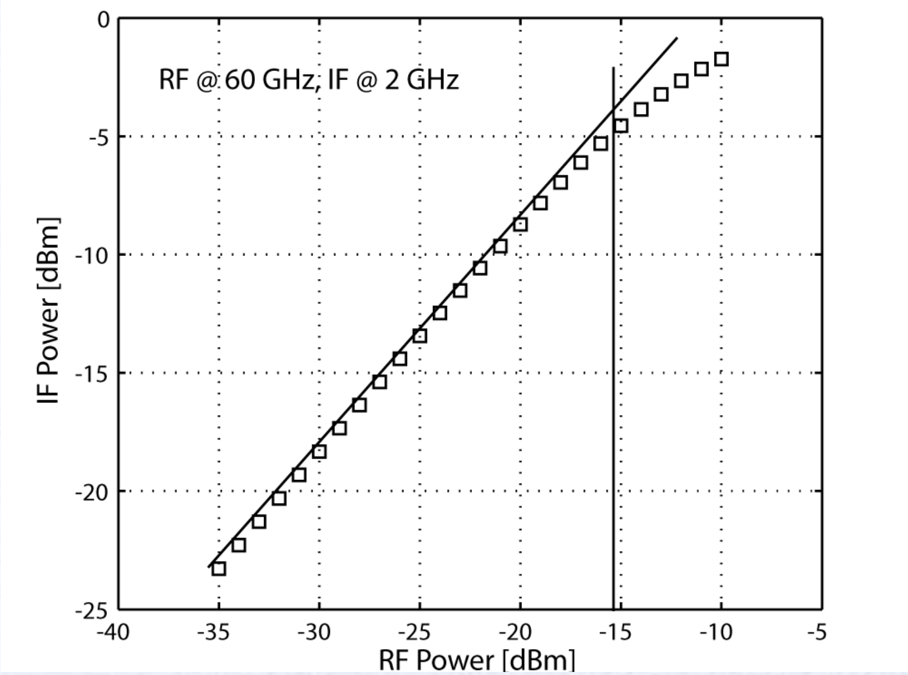
Highly Integrated Front-End



- Includes LNA, mixer, frequency doubler, VCO, LO and IF buffers.
- Die size: 3.8mm^2

Measured Performance



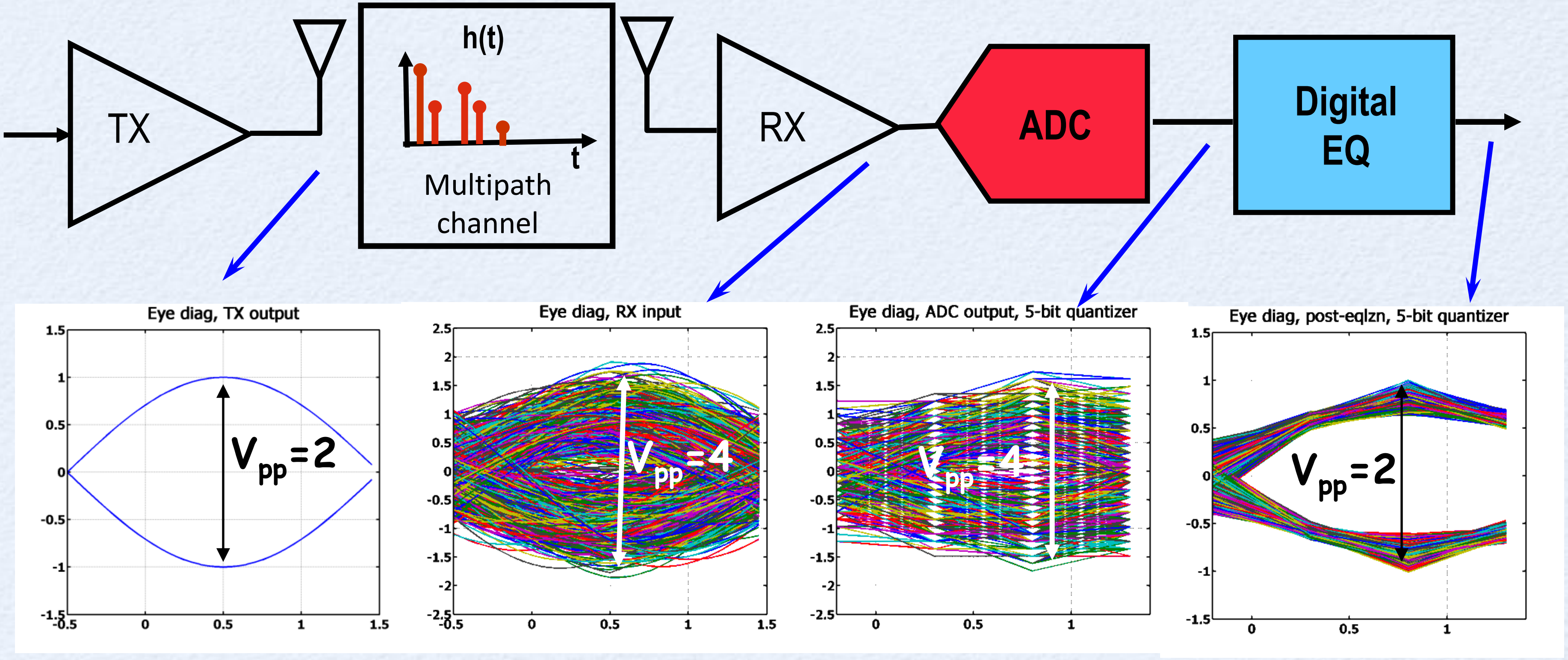


- Input referred P_{1dB} is -15.8dBm
- Phase noise of –86dBc/Hz at 1MHz offset.
- Total power dissipation is 64mA from a 1.2V supply.

Handling 7 GHz of Bandwidth

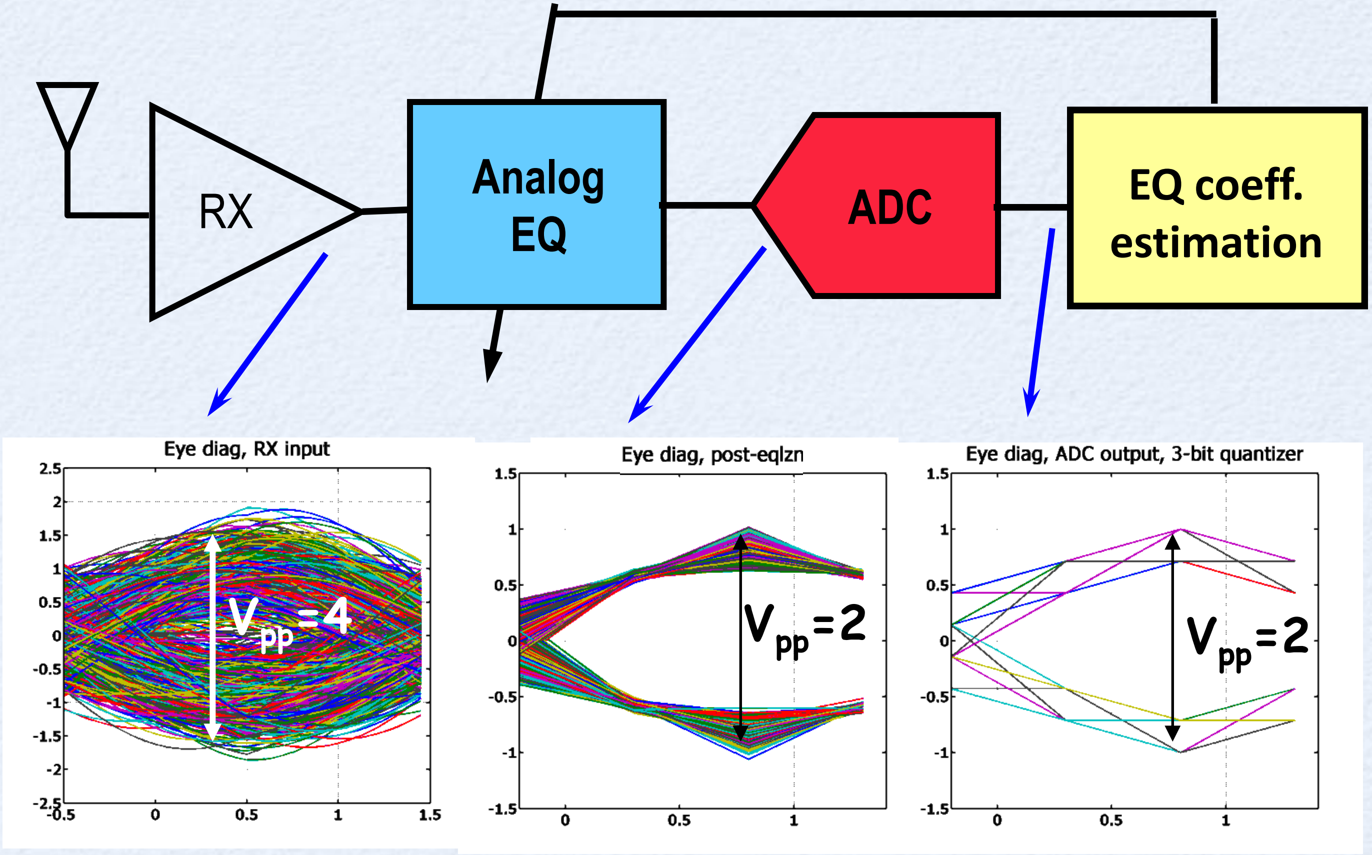
- “Simple” modulation scheme like FSK simplifies circuit requirements
- Linearity, PA efficiency, noise, phase noise
- But, still need high-speed ADCs (power hungry)
- Minimize ADC resolution to solve power problem
  - From 6 bit to 4 bit 10x power reduction possible

Effect of Multipath



- Digital equalization removes ISI but need more bits in ADC

Analog to the Rescue



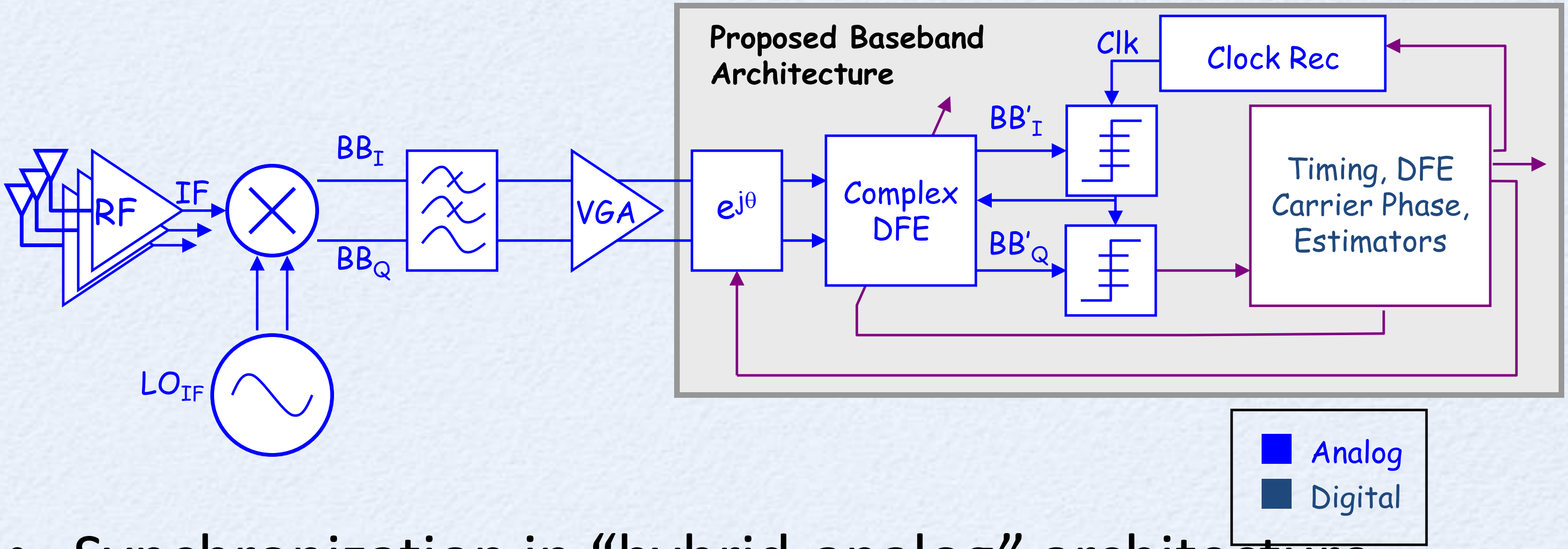
RX

Analog EQ

ADC

EQ coeff. estimation

“Hybrid-Analog” Architecture

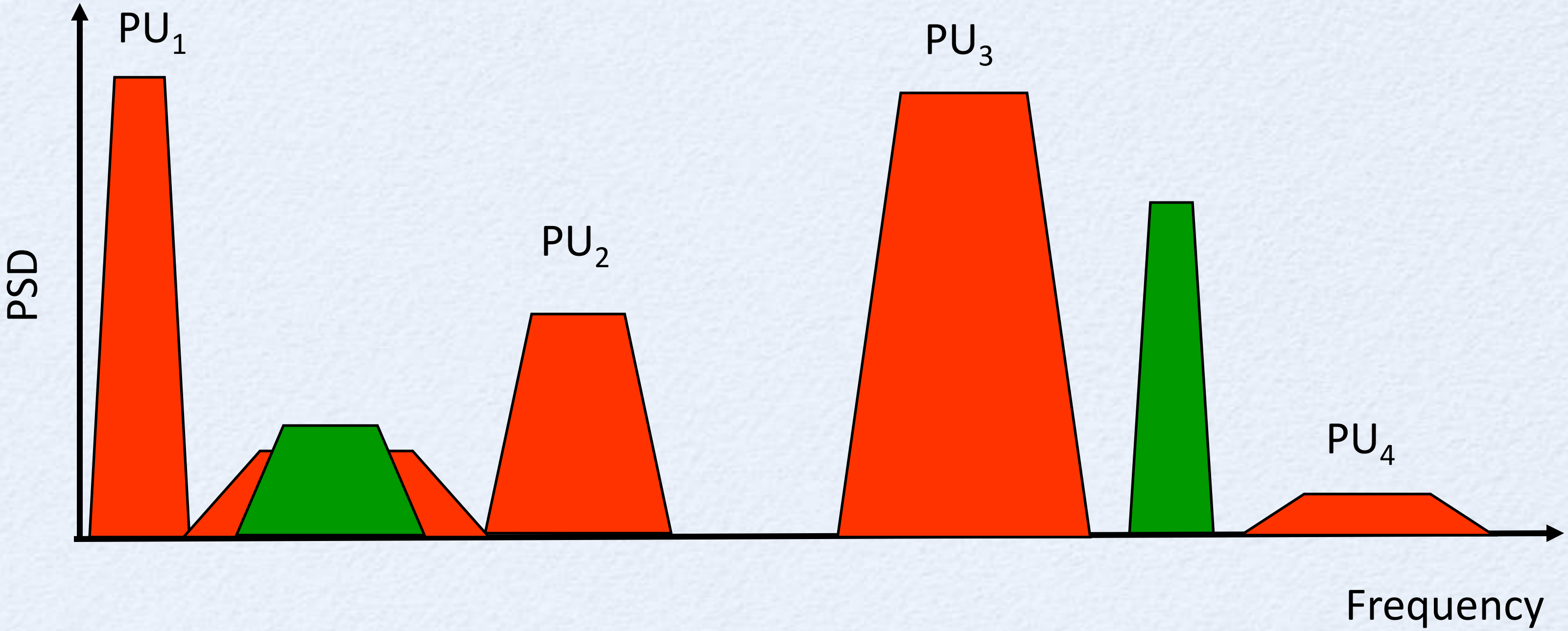


- Synchronization in “hybrid-analog” architecture
  - ESTIMATE parameter error in digital domain
  - CORRECT for parameter error in analog domain
- Greatly simplifies requirements on power-hungry interface ckts (i.e. ADC, VGA)
  - Additional analog hardware is relatively simple

Unused Reserved Tables

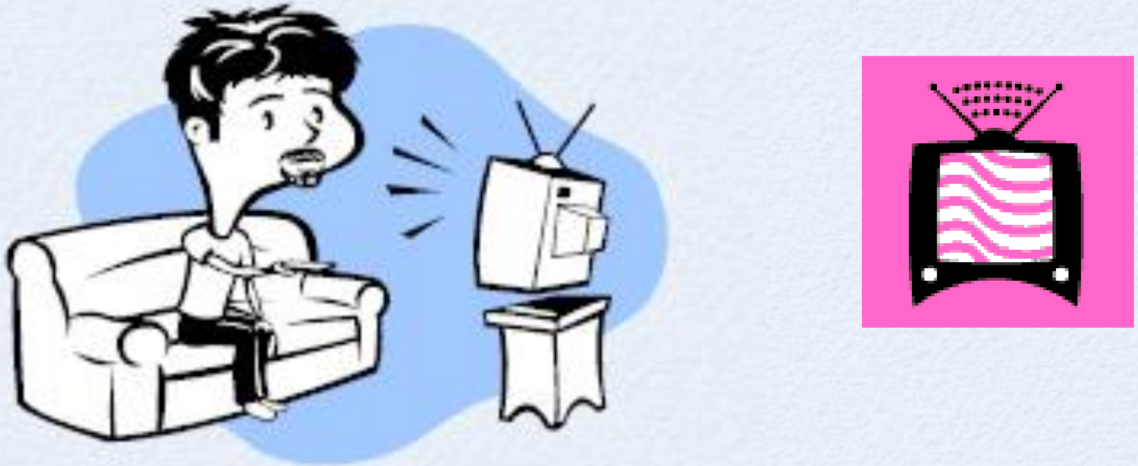
COGNITIVE RADIO

How does a CR operate?



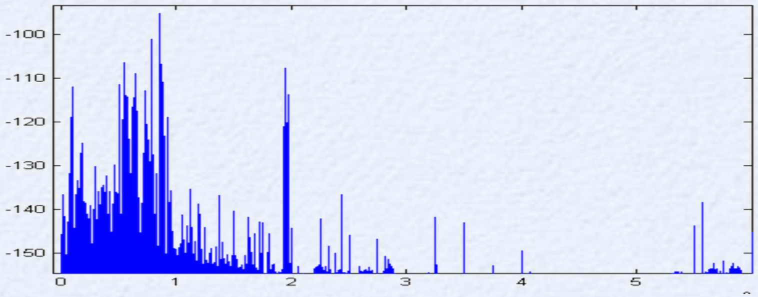
- **sense** the spectral environment over a wide bandwidth
- reliably **detect** presence/absence of primary users
- **transmit** in a primary user band only **if detected as unused**
- **adapt** power levels and transmission bandwidths to avoid interference to any primary user

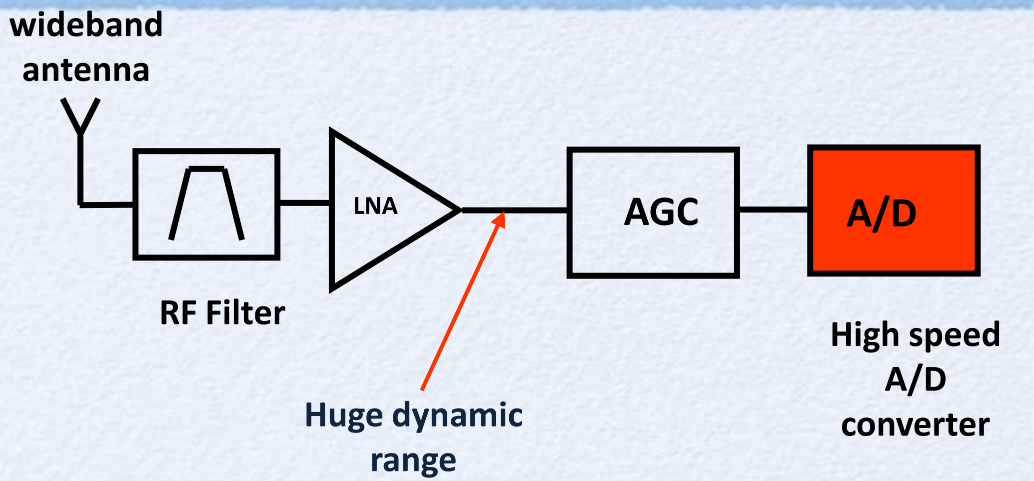
Can you hear me?



- If a CR cannot detect the presence of a primary user, that doesn’t mean it’s unused!
- Broadcast receiver is a classic example. The CR may be in a signal fade nearby and jam a TV station since it thinks no one is

Wideband Sensing Radio





wideband antenna

RF Filter

LNA

Huge dynamic range

AGC

A/D

High speed A/D converter

Challenging specifications:

Multi-GHz A/D -> Nyquist sampling

High A/D resolution (> 12 bits)

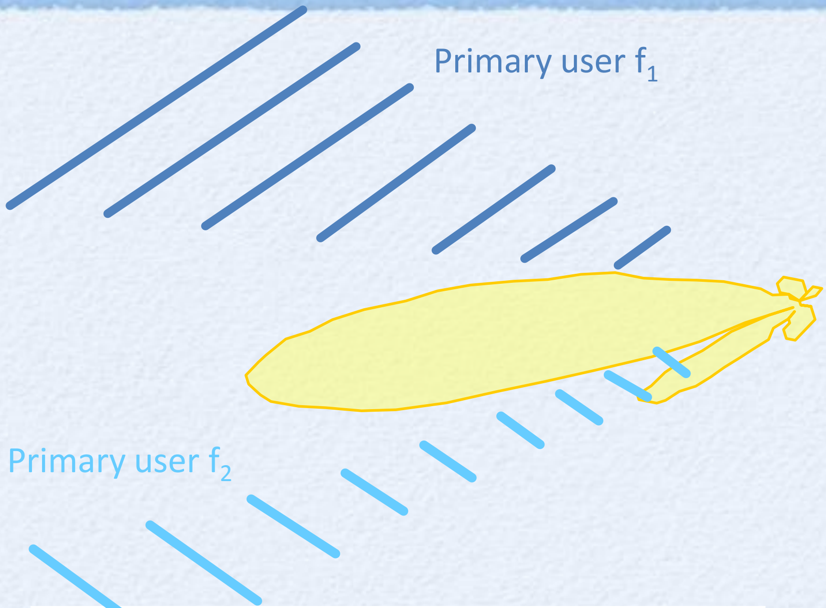
Dynamic range reduction:

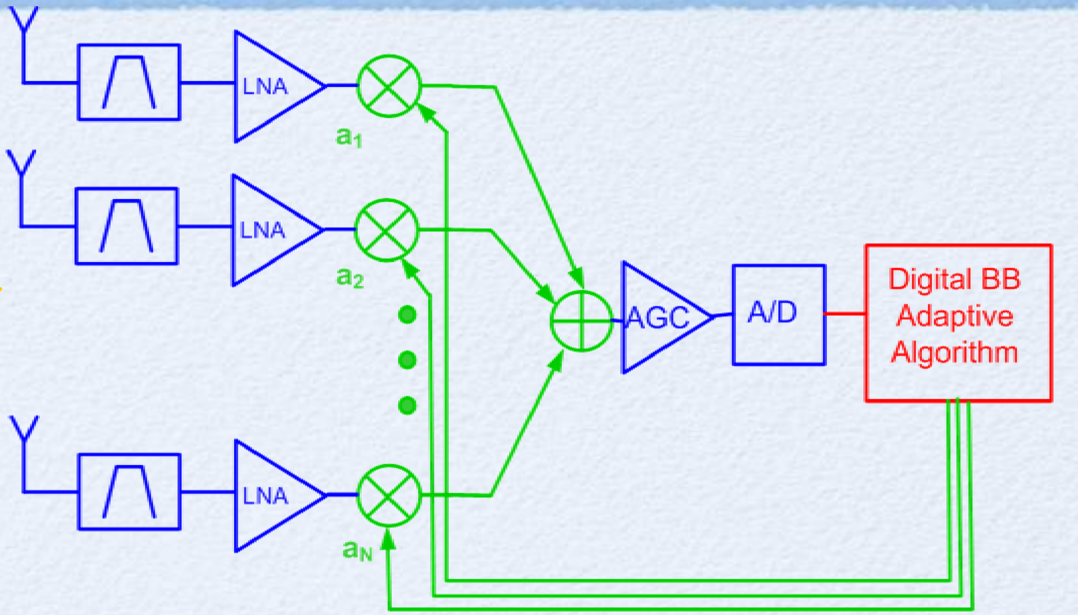
Frequency: RF MEMS filter bank

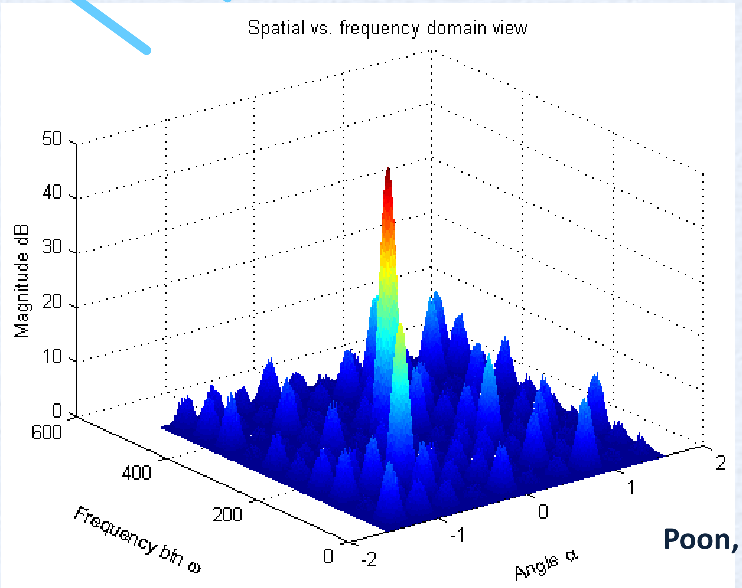
Time: Active cancellation

Spatial: Filtering using multiple antennas

Spatial Filtering







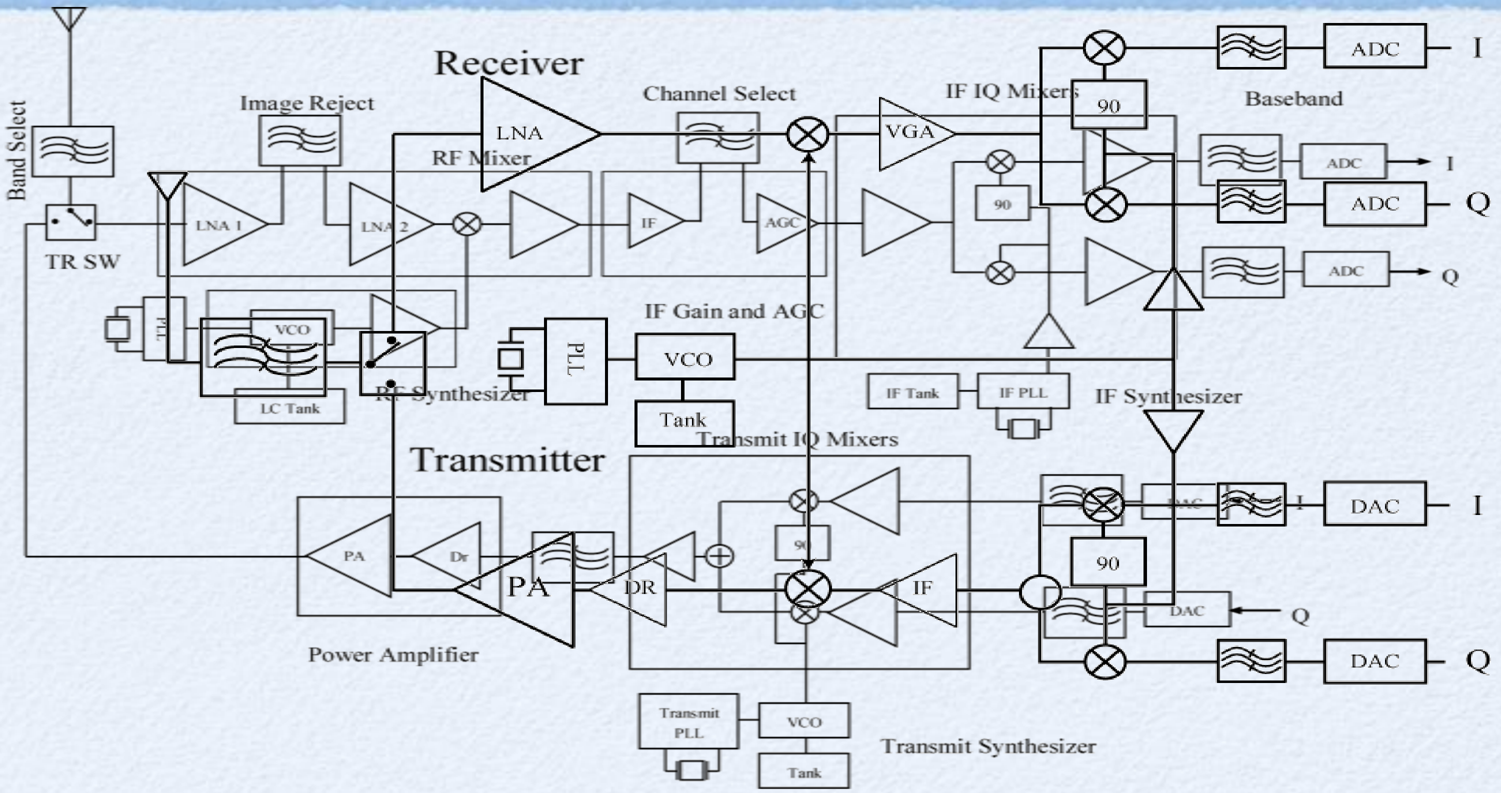
- Point antenna array at cognitive radio transmitter – avoid interferers
- Combine antenna outputs in analog domain to reduce dynamic range

Poon, Tse, Brodersen[2004]

CR Challenges

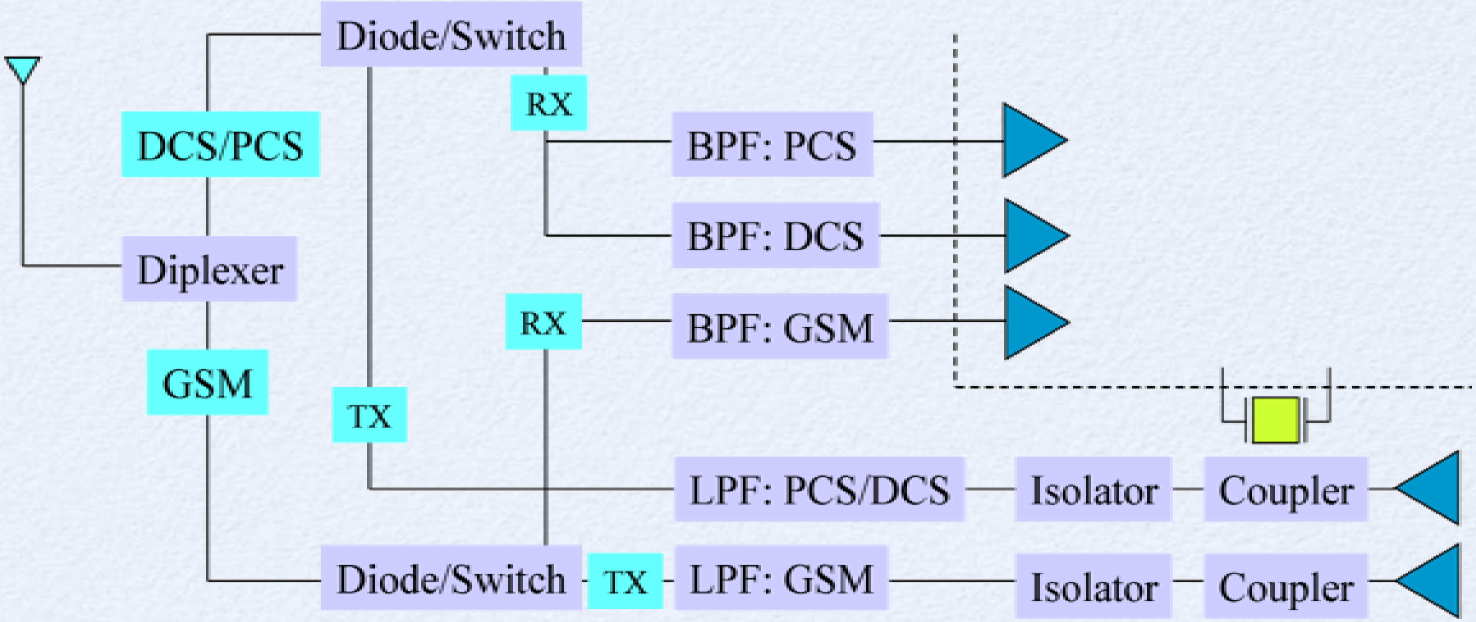
- Wide bandwidth circuits to allow for more opportunity to find unused spectrum
- Co-existence with primary users requires a high dynamic range required over these wide bands
- Need highly reliable sensing of even weak primary users

From Super-Het to Low IF



- Fully integrated radios low-IF or zero-IF to reduce IF SAW filters
- RX FE integrated in a single chip. PA is a separate chip or module.
- Radio optimized for a specific standard (image rejection, linearity, filtering, bandwidth)

Typical External Components



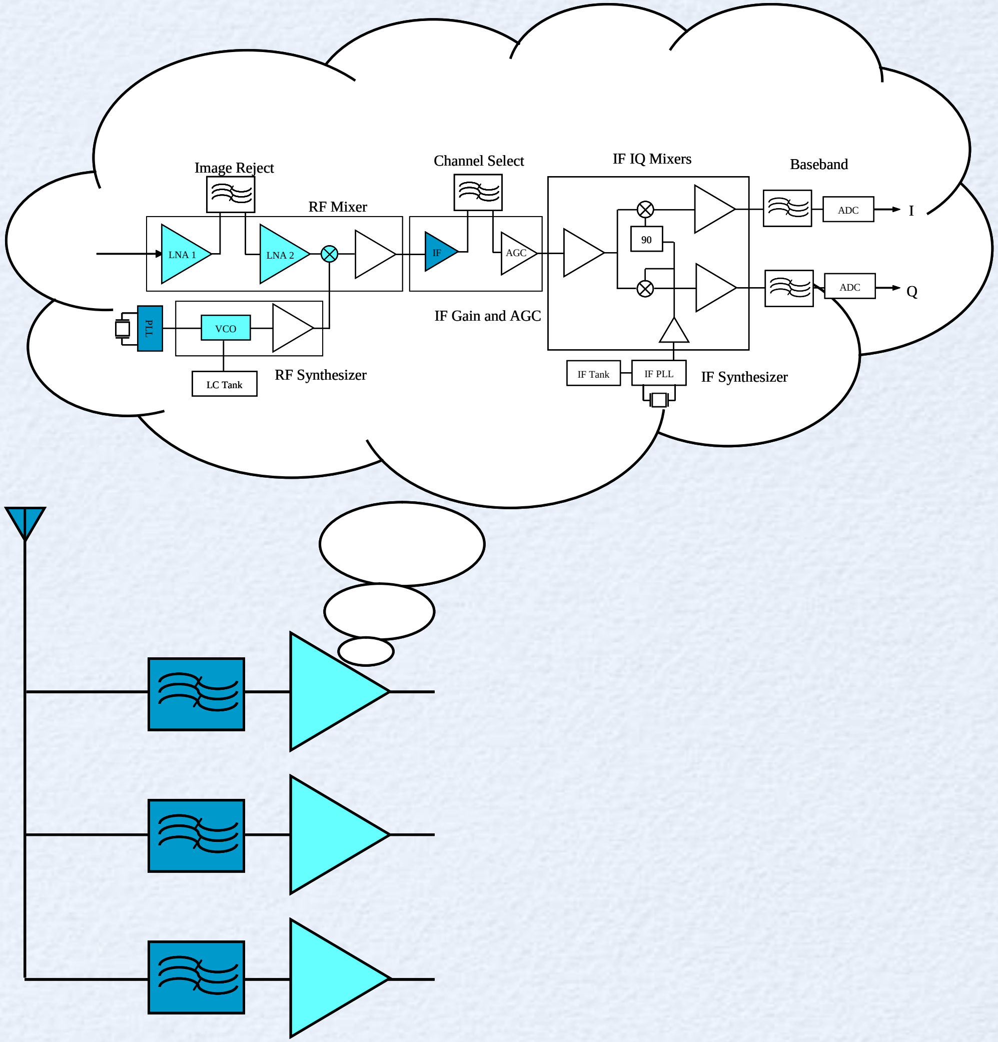
- Systems heavily dependent on external components on the front end: SAW filters, switches, directional couplers, matching networks, pin diode, diplexers …
- Many of these components are expensive (high Q) and narrowband

HIGH DYNAMIC RANGE BROADBAND CIRCUIT BUILDING BLOCKS

Can CMOS do it?

Multiplicity of Standards

- Cellular voice: GSM, CDMA, W-CDMA, CDMA-2000, AMPS, TDMA…
- Same standard over multiple frequency bands (4-5 GSM bands exist today)
- Data: 802.11x, Bluetooth, 3G, WiMax…
- A typical handheld computer or laptop should be compatible with *all* of the above standards

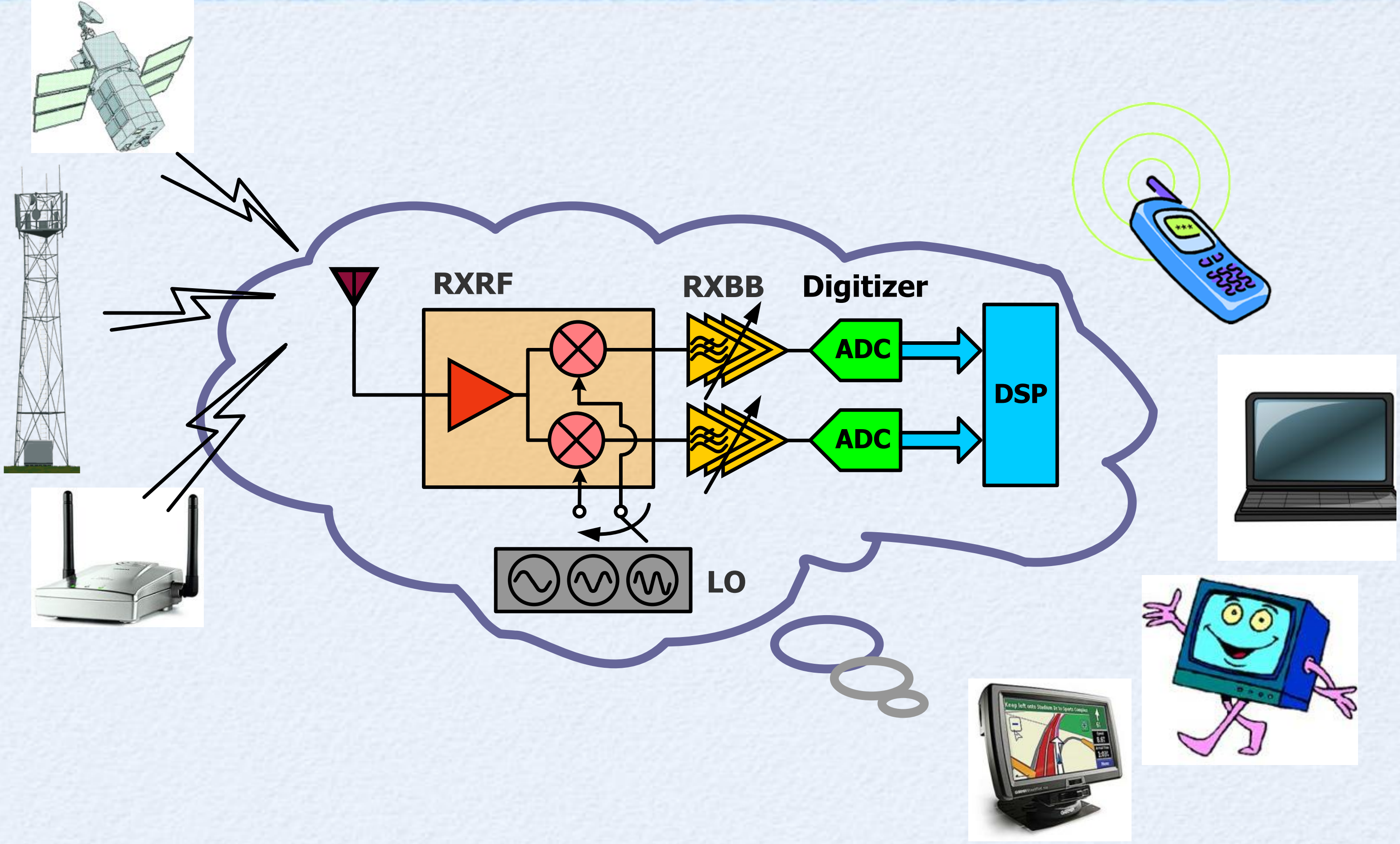


SDR, Universal, Cognitive,Dynamic?

- Loose definitions:
  - SDR: Reprogram the baseband
  - Universal: Multi-standard
  - Multi-mode: short/long range, high/low data
  - Cognitive: Ability to sense spectrum and use it
  - Dynamic: Ability to alter bias currents to tradeoff performance versus power consumption
- RF front-end of future should support all of the above functionality

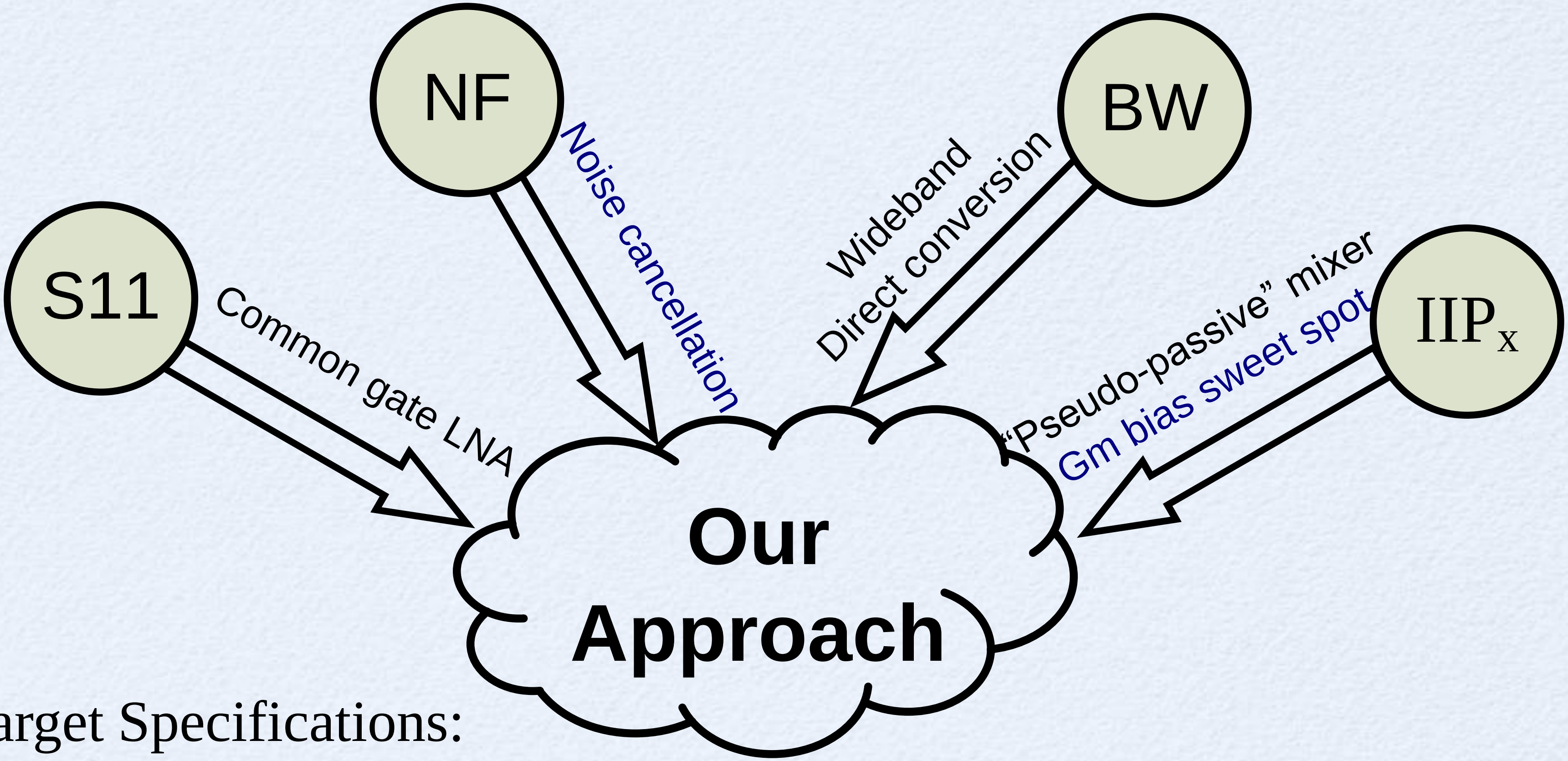
COGUR: Cognitive Universal Radio

COGUR Front-End



low noise/power, high dynamic range/reconfigurability

COGUR Approach

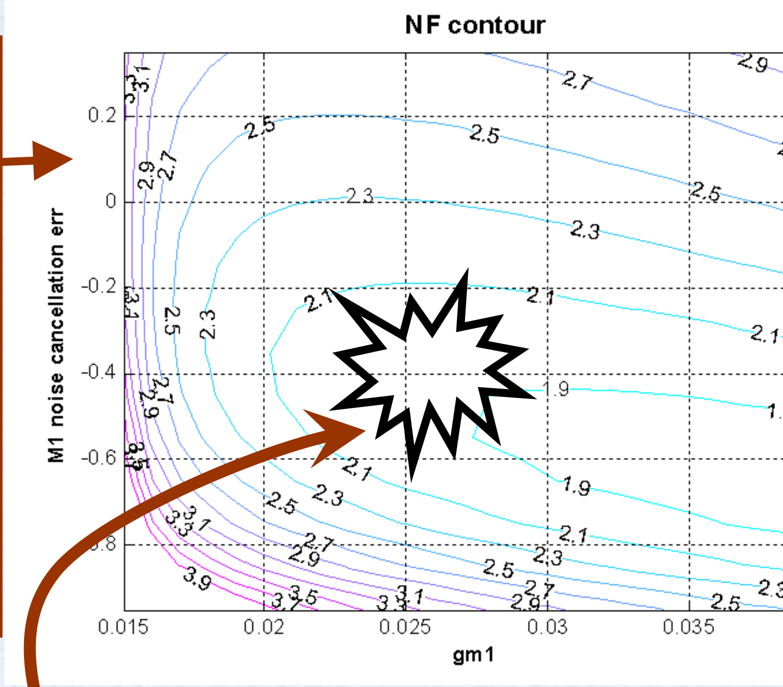


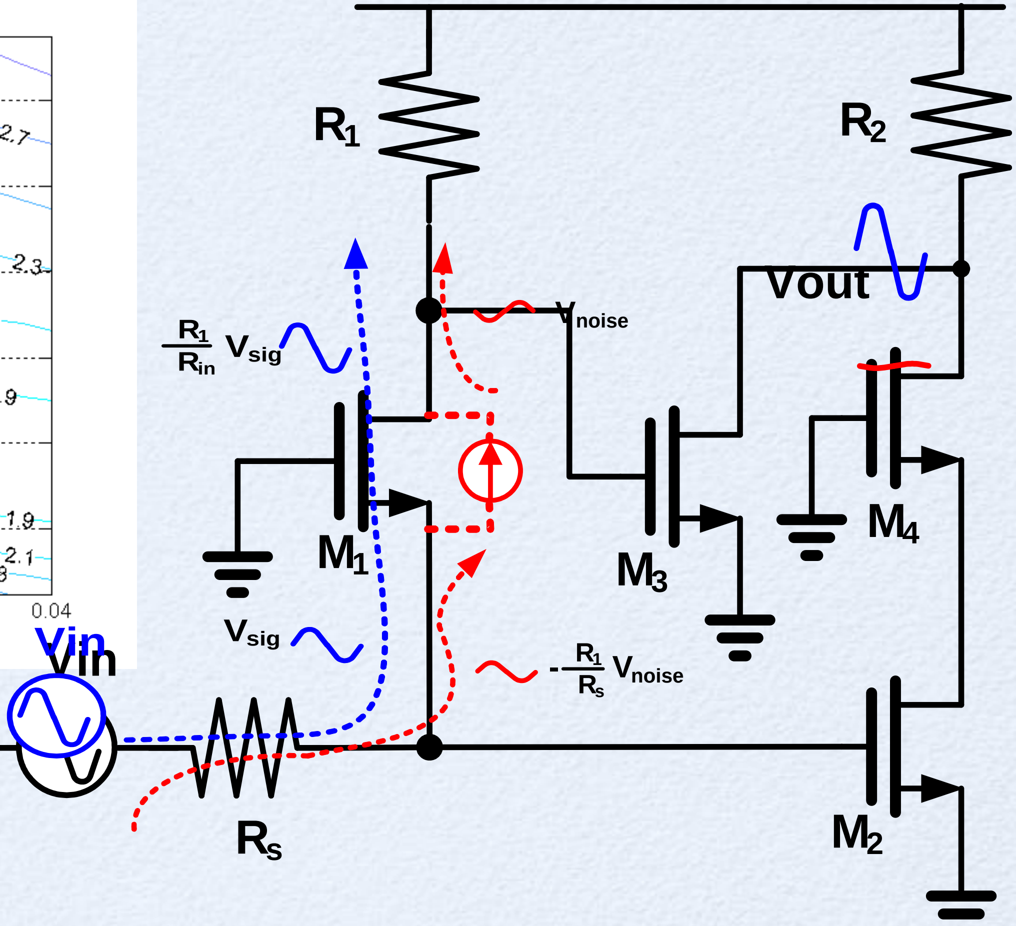
Target Specifications:

- BW 0.8~2.4GHz
- Gain > 25dB, NF < 2.5dB
- IIP3 > 0dBm, IIP2 >55dBm

Noise & Disto Cancellation LNA

M1 noise full cancellation





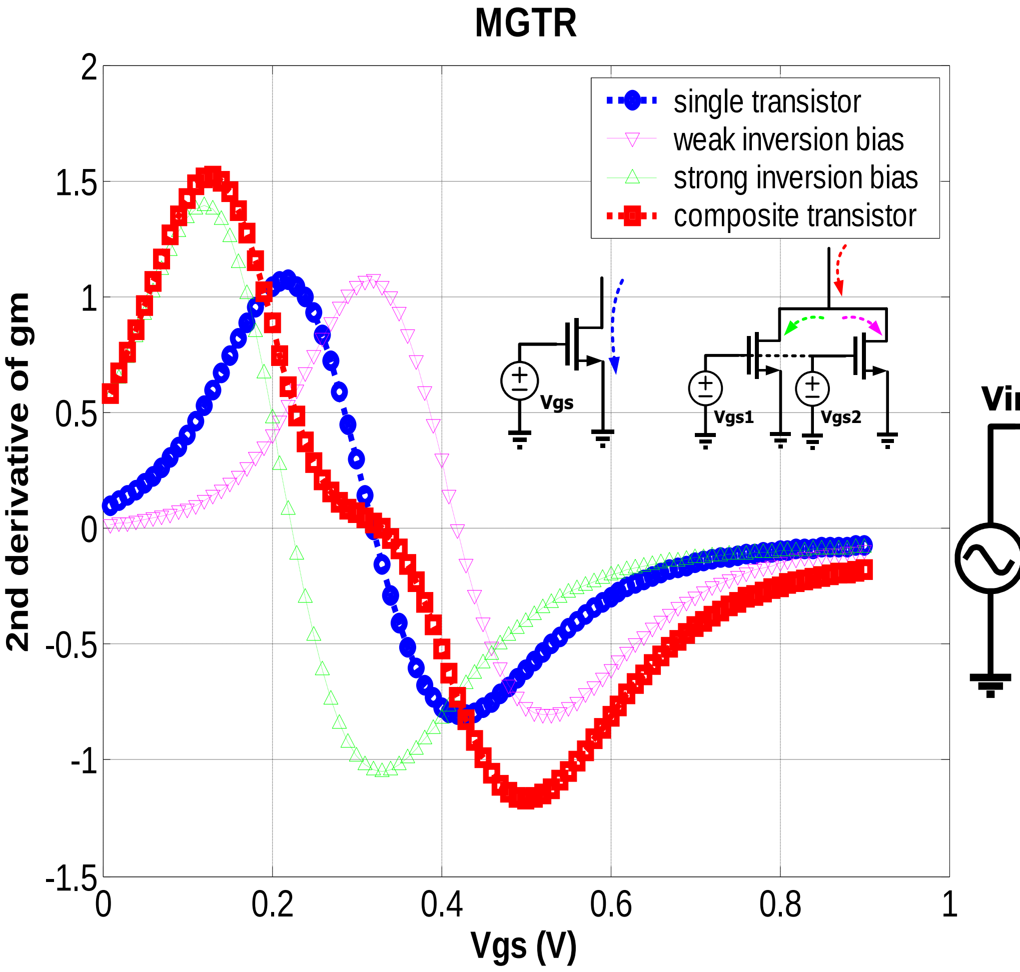
Optimal choice subject to fewer design parameter variations

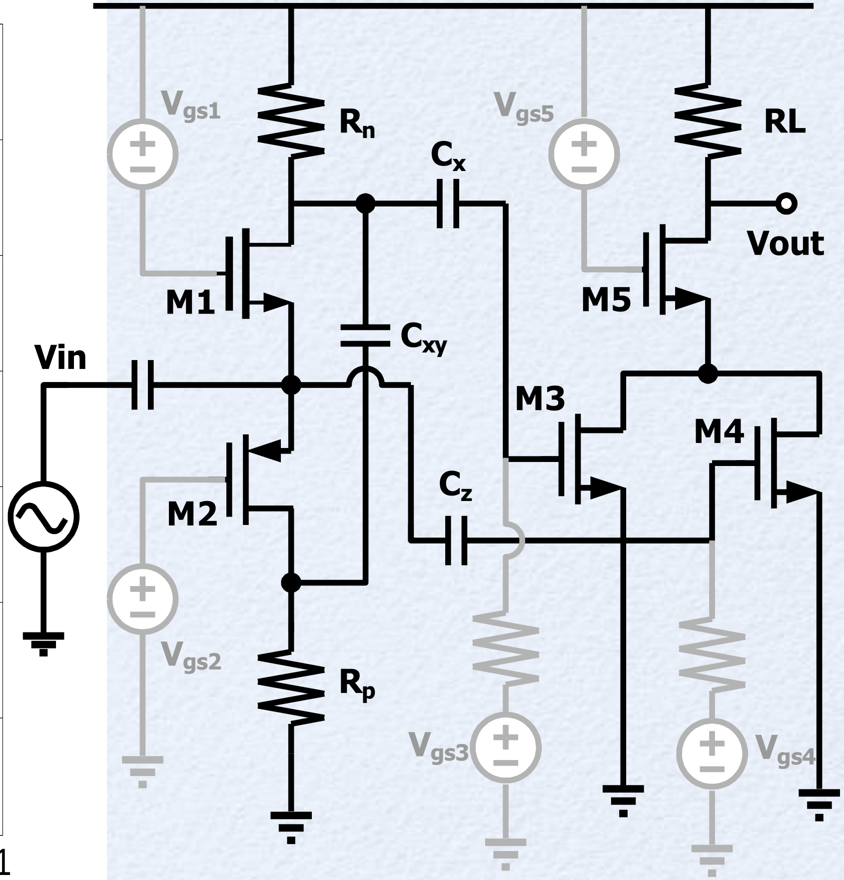
$$Vout = g_{m2} * V_{sig} + g_{m3} * \frac{R_1}{R_{in}} V_{sig} + g_{m3} * V_{noise} - g_{m2} * \frac{R_1}{R_s} V_{noise}$$

Motivated by [Bruccoleri, *et al.*, ISSCC02]

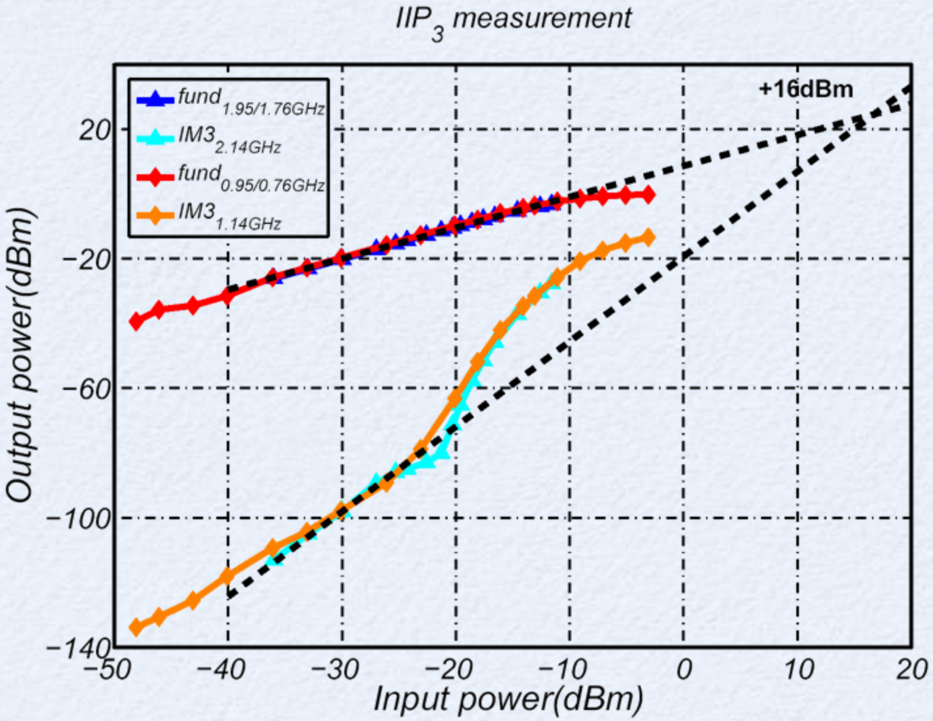
MGTR (Multi-Gated Transistor)

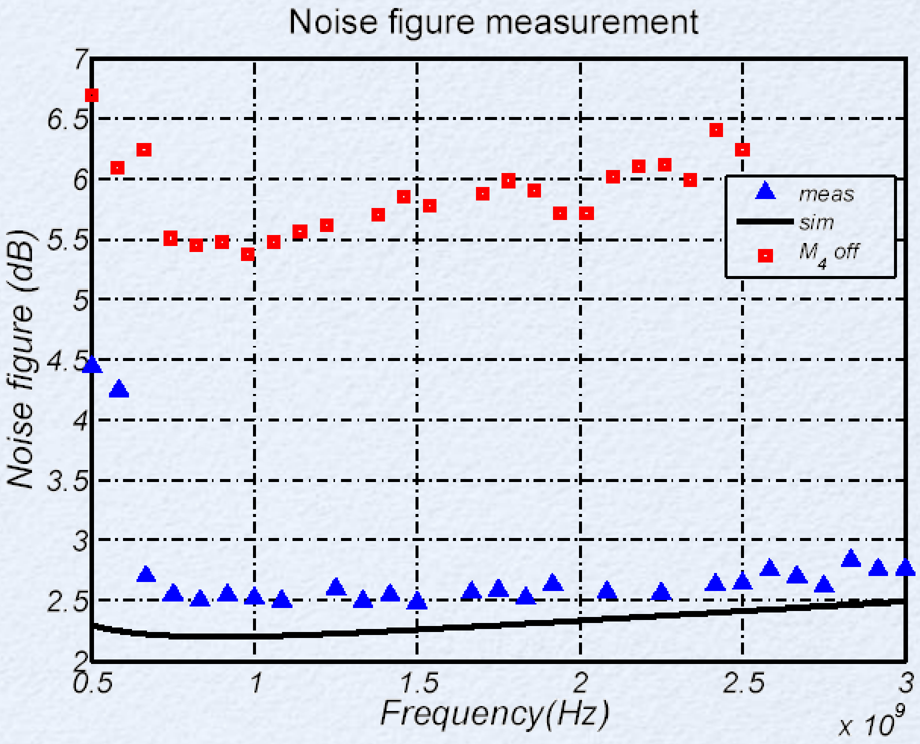
Composite transistors to reduce sweet spot bias sensitivity

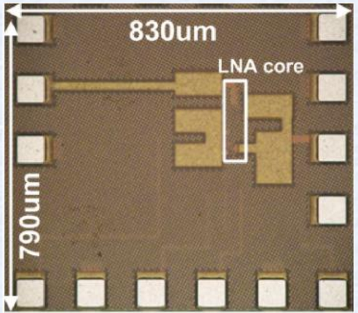




Measured Noise and Linearity


IIP_3 measurement

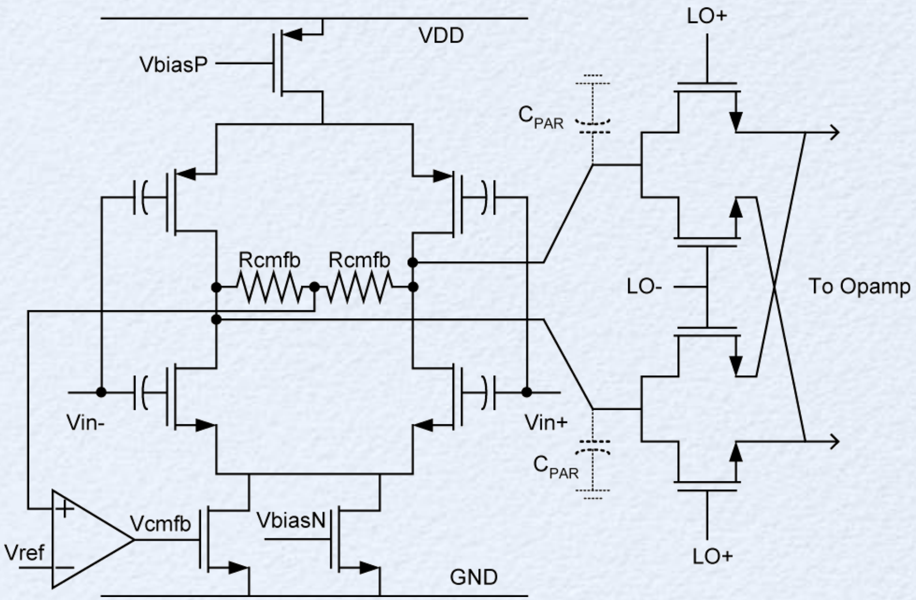

Noise figure measurement



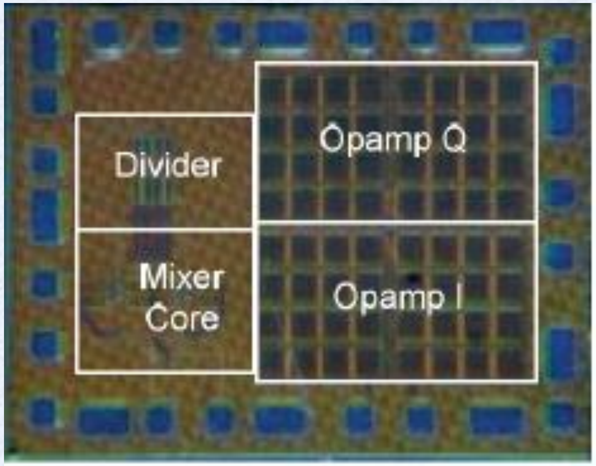
- Record linearity of +16 dBm for out of band blockers.
- Linearity works over entire LNA band.

Wideband I/Q Passive Mixers

Process Technology	0.13 CMOS	
Input Frequency Range	0.7GHz – 2.5GHz	
First Filter Pole	250 kHz	
Total Bias Current	20mA-24mA (1.5 V)	
Conversion Gain	38.5dB	
IIP_3@1MHz Offset	900 MHz	2.1 GHz
	+11 dBm	+12 dBm
IIP_2@1MHz Offset	+66dBm	+64 dBm
NF@1MHz IF	10dB	10.5 dB
1/f Corner	10 kHz	26 kHz
LO-RF Leakage	-74dBm rms	

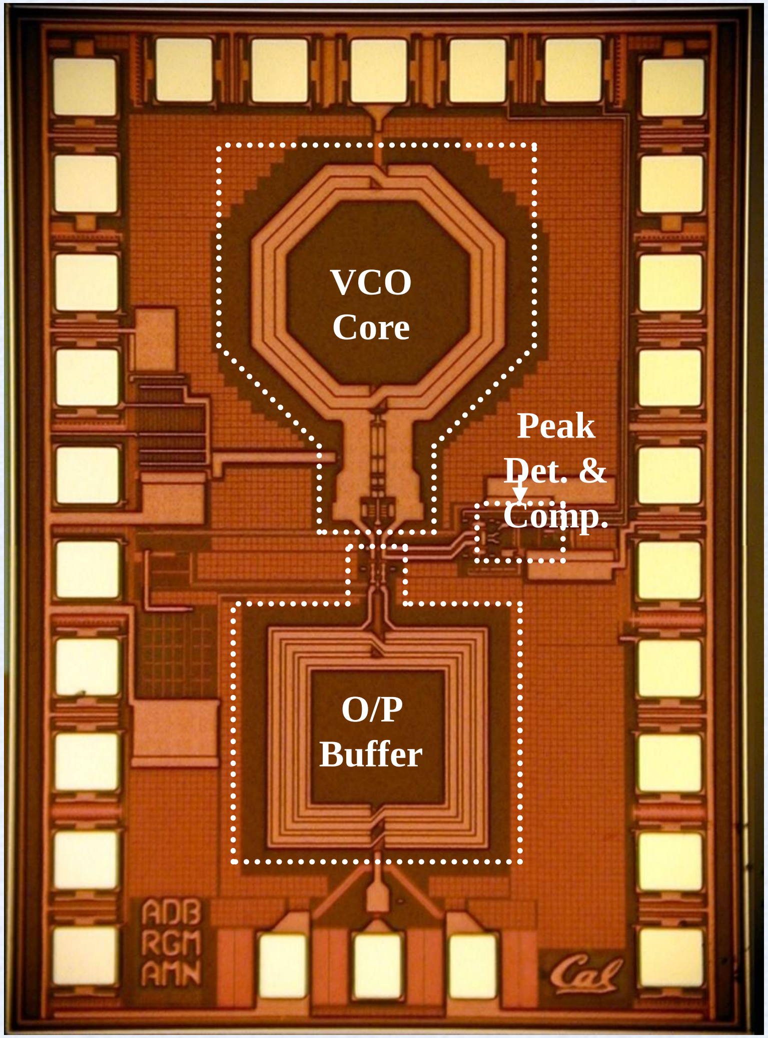


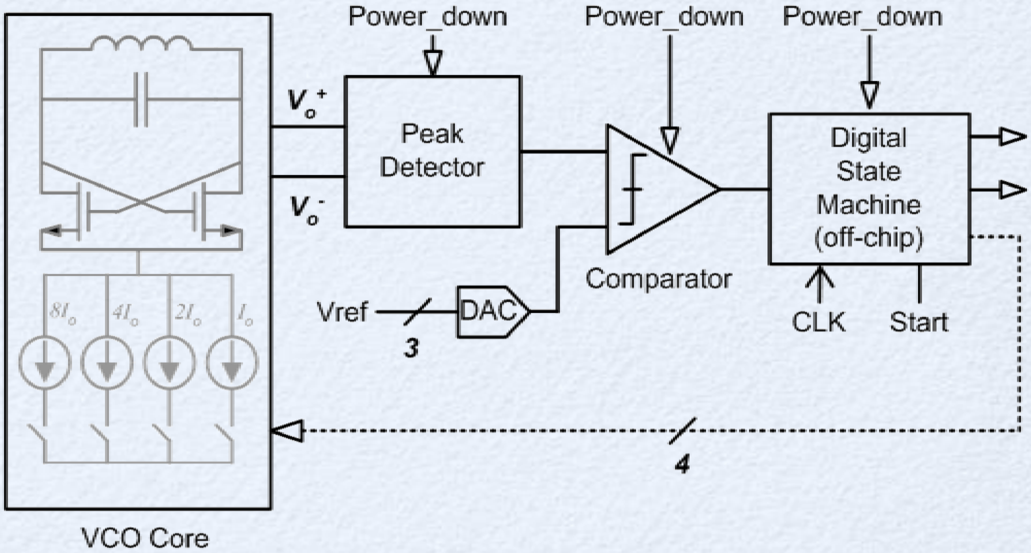
- Complementary input for higher gm and linearity
- Passive switching to get low 1/f noise
- Implemented as a I/Q mixer with integrated on-chip divider



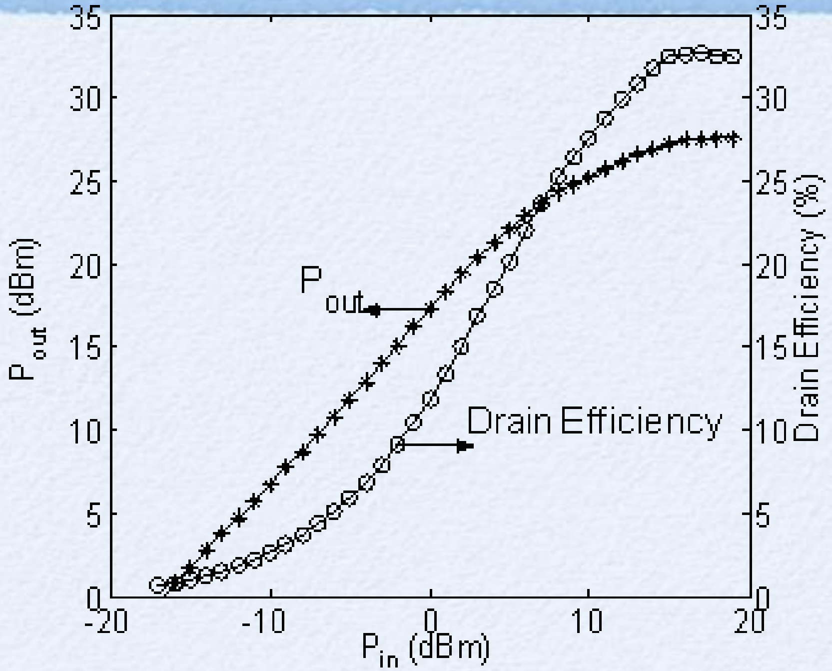
Broadband “Universal” VCO

- A 1.8 GHz LC VCO (0.18µm CMOS)
- 1.3 GHz Tuning Range
- Mixed-signal Amplitude Calibration
- Phase noise of –104.7dBc/Hz at a 100kHz
- 3.2mA from a 1.5V supply

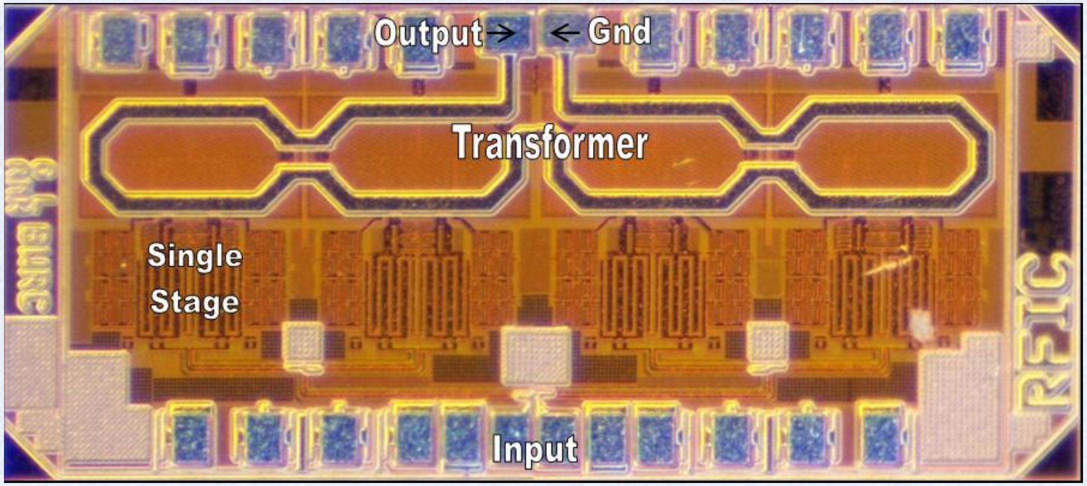


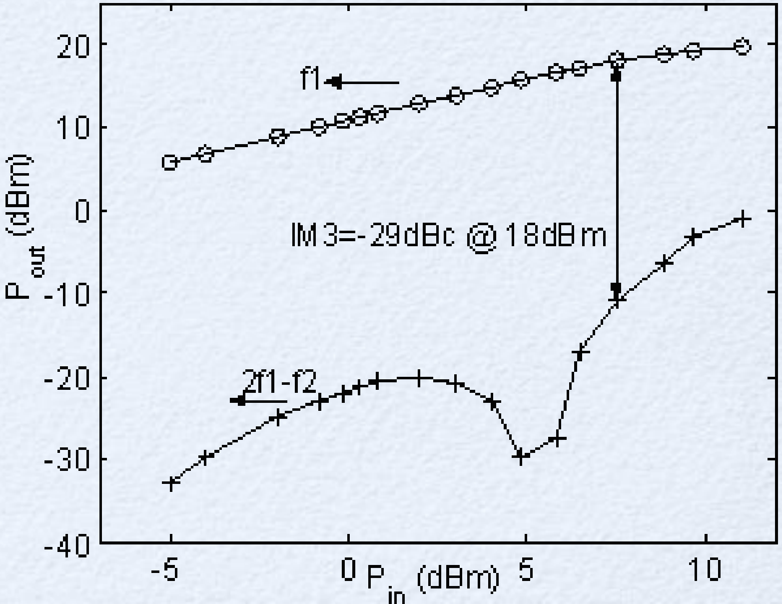


Integrated Linear CMOS PA

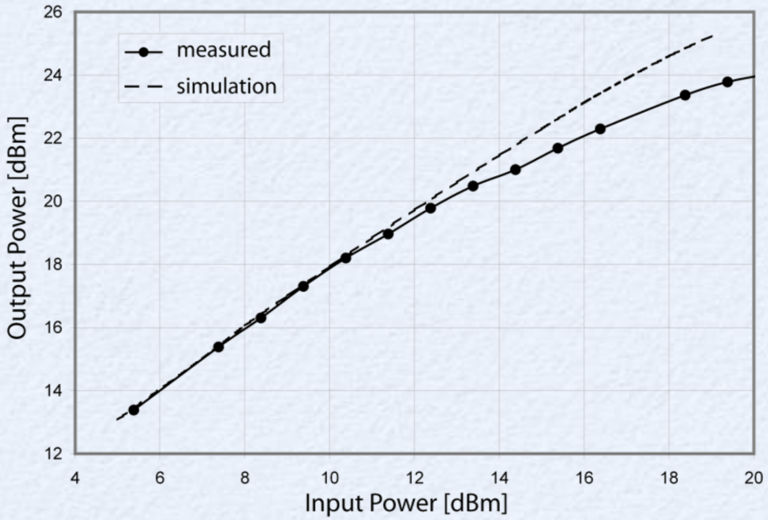


- Fully 130nm CMOS integrated prototype
- 27 dBm (30% efficiency)
- Linear mode: 24 dBm (25%)
- No external passives

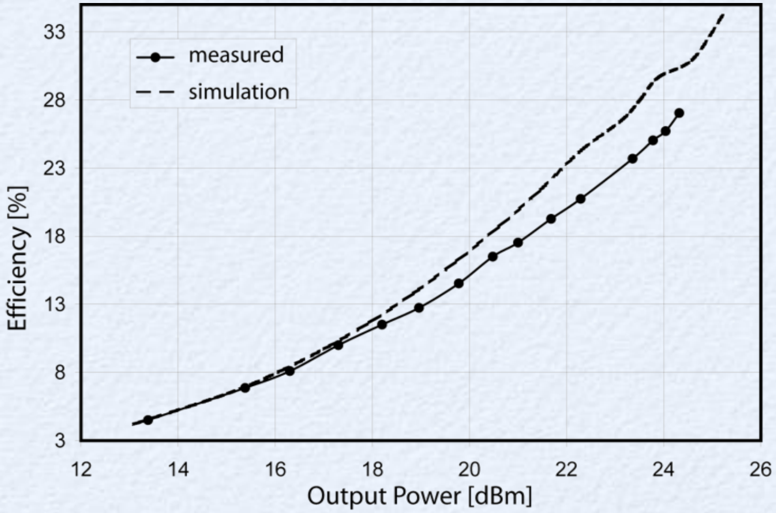


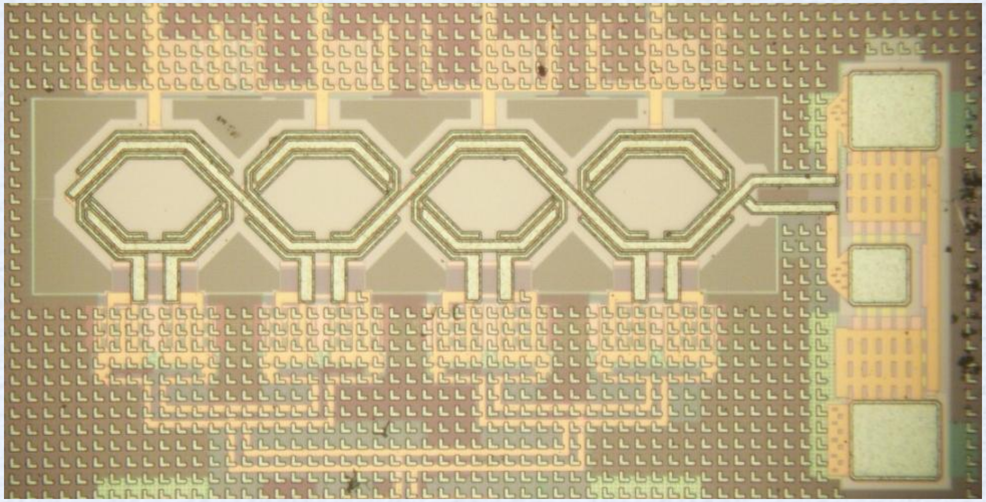


Prototype PA in Digital CMOS



- Four stage differential design
- Fully integrated matching
- Thin oxide 90nm transistors
- 24 dBm, 27% efficiency
- 1V Power Supply





Conclusions

- FCC has provided exciting new opportunities for new radio systems
  - UWB
  - Unlicensed 7 GHz at 60 GHz
  - Cognitive Radios
- These provide new circuit challenges dealing with high frequencies, wide bandwidths and large dynamic ranges
- The key to the solution will require new approaches to analog and digital partitioning

Acknowledgements

- Vodafone Foundation
- BWRC member companies
- DARPA TEAM Program
- UC Discovery and MICRO programs
- Students:
  - David Soble, Danijela Cabric (60 GHz, CR)
  - Ian O’Donnel, Stanley Wang, Mike Chen (UWB)
  - Wei-Hung Chen, Gang Liu, Debo Chowdhury, Nuntachai
  - Poobuapheun, Zhiming Deng (COGUR)
  - Sohrab Emami and Chinh Doan (60 GHz)
  - Ehsan Adabi, Babak Heydari (60 GHz Gen2)