Radio Research Directions

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Outline

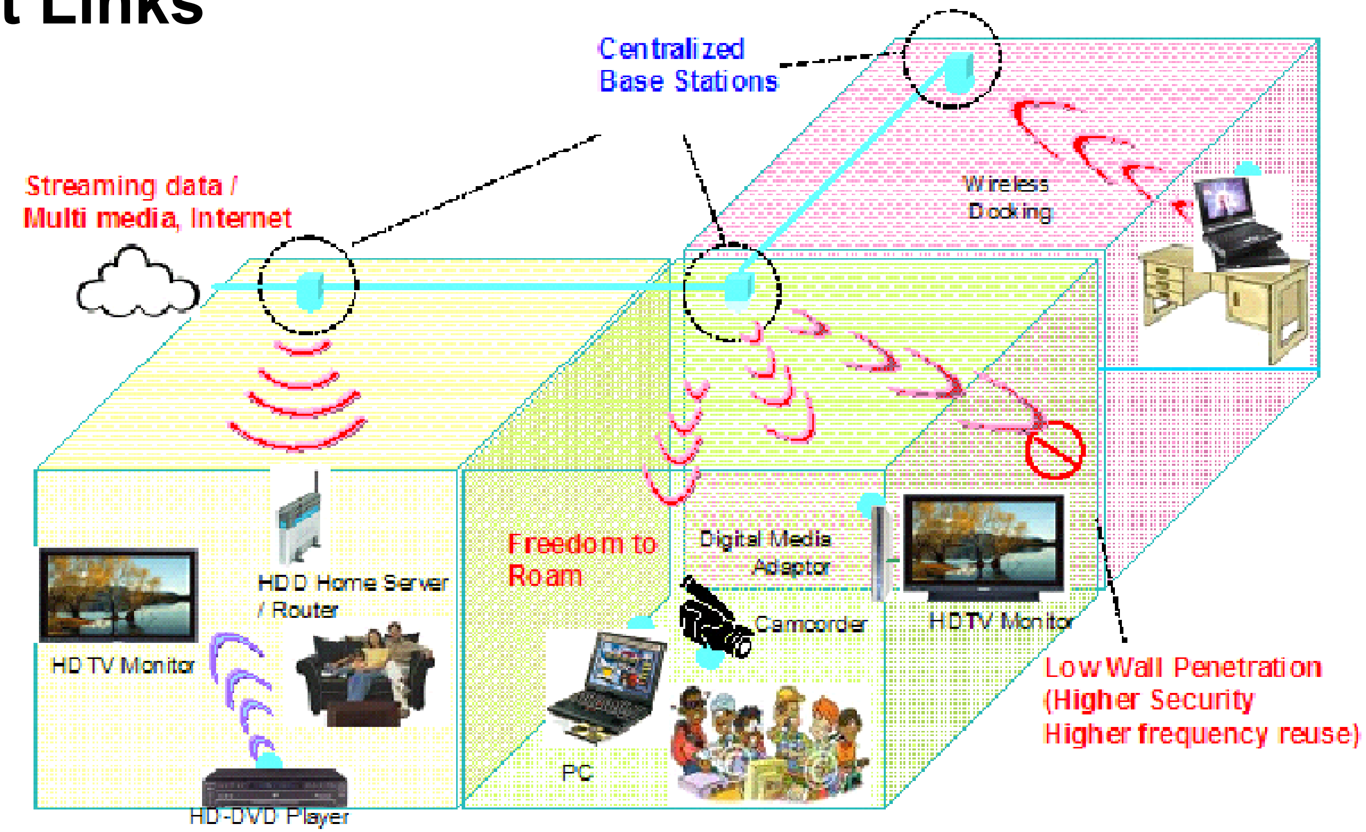
- Introduction
- Millimeter-Wave Transceivers
  - Applications
  - Challenges
  - Examples
- Cognitive Radios
  - Challenges
- Conclusion

Nature of Our Radio Research

- Target highly-integrated transceivers with minimal number of external components
- Address tough problems: higher frequency, wider bandwidth, lower power consumption, …
- Develop new architectures, circuits, devices that solve these problems
- Realize ideas in standard CMOS technology and verify by experimentation
- Examples of past work:
  - 900-MHz/1.8-GHz Transceivers for Cellular Telephony
  - 2.4-GHz and 5.2-GHz WLAN Transceivers
  - 3-6 GHz UWB Transceivers
  - 5-GHz RX for MIMO
  - 60-GHz Transceivers

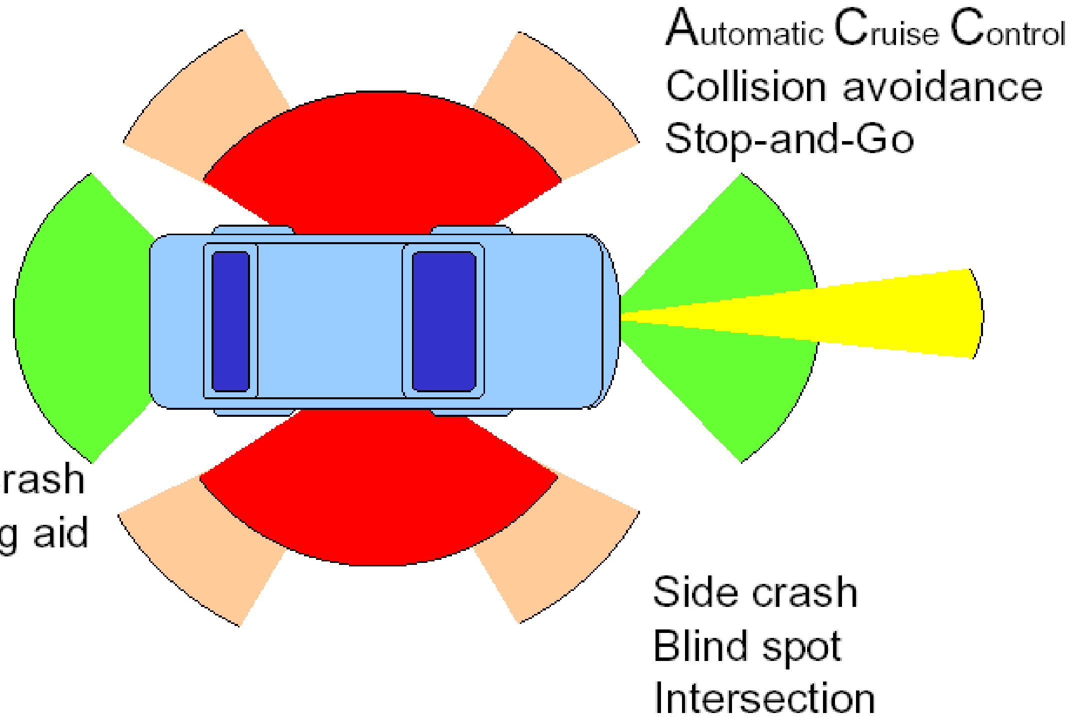
Why the interest in mmWaves?

- Unlicensed band: 57 GHz – 64 GHz offers possibility of high-data rate communications:
  - High-Definition Video Streaming
  - Fast Links



Why the interest in mmWaves?

- **Automotive Radar (60-77 GHz)**

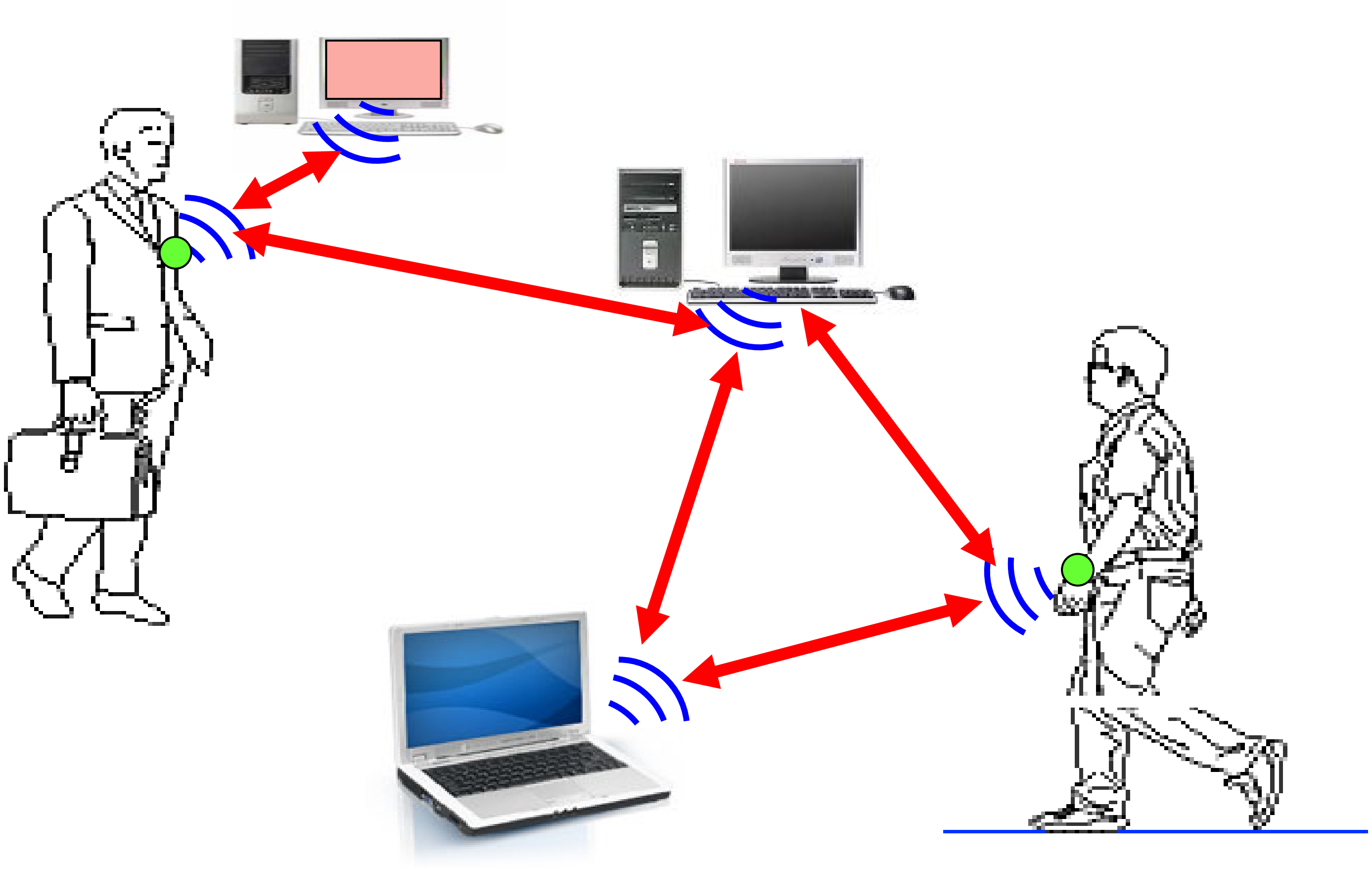


Why the interest in mmWaves?

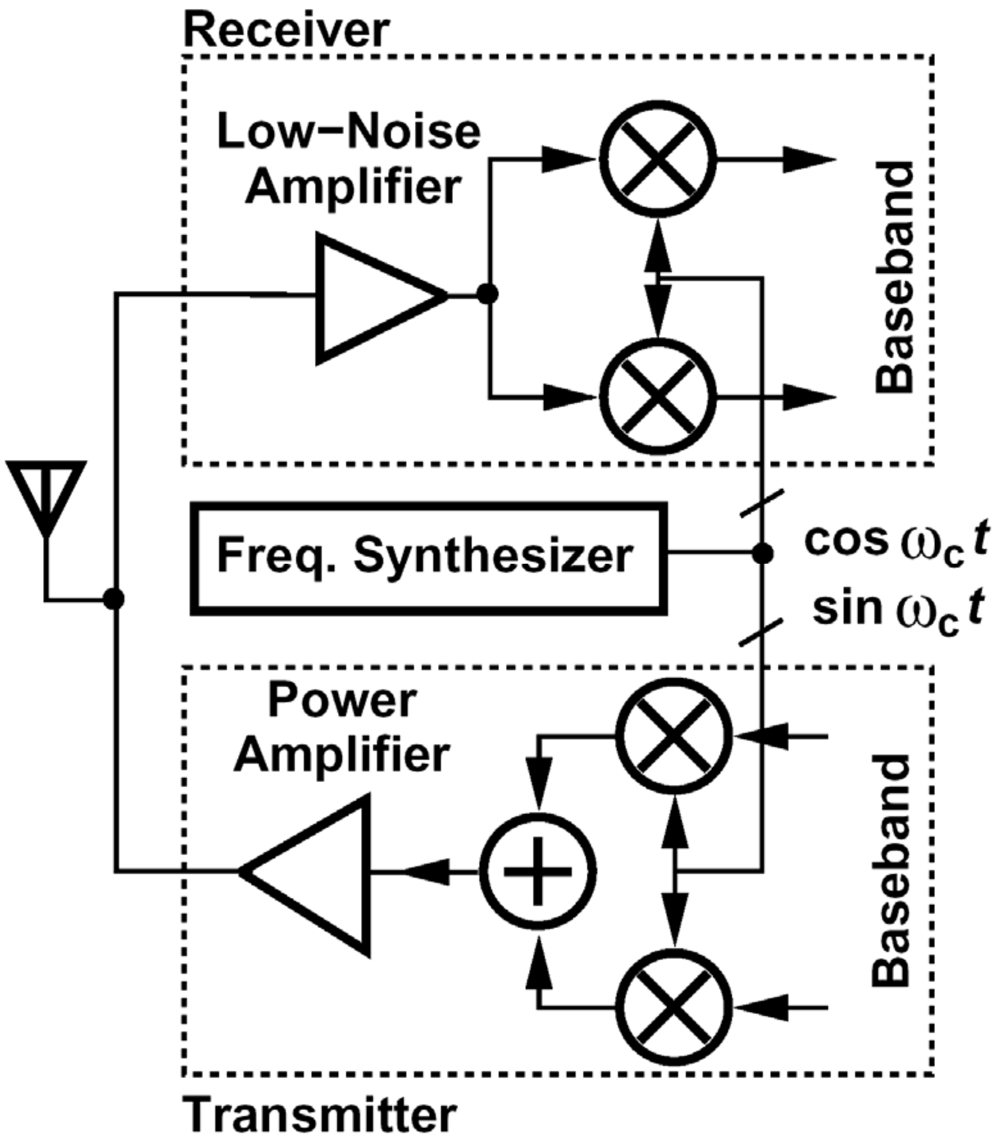
- mmWave Imaging (> 100GHz)

Networks with High Redundancy

- **Line-of-sight propagation a serious issue**

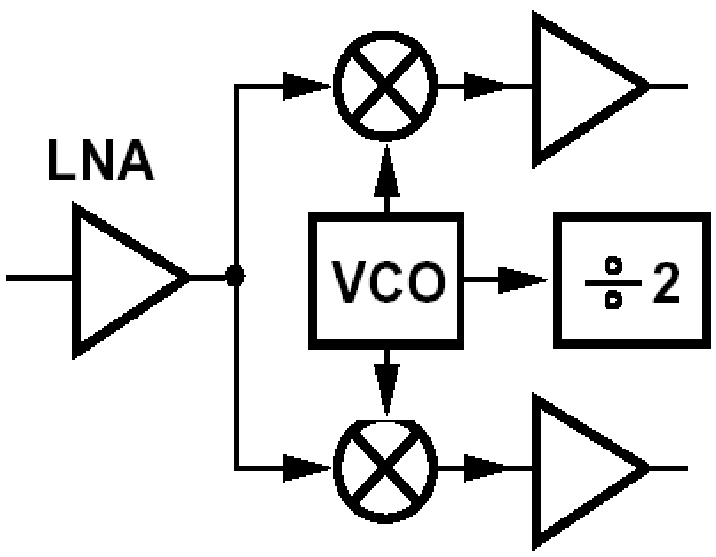


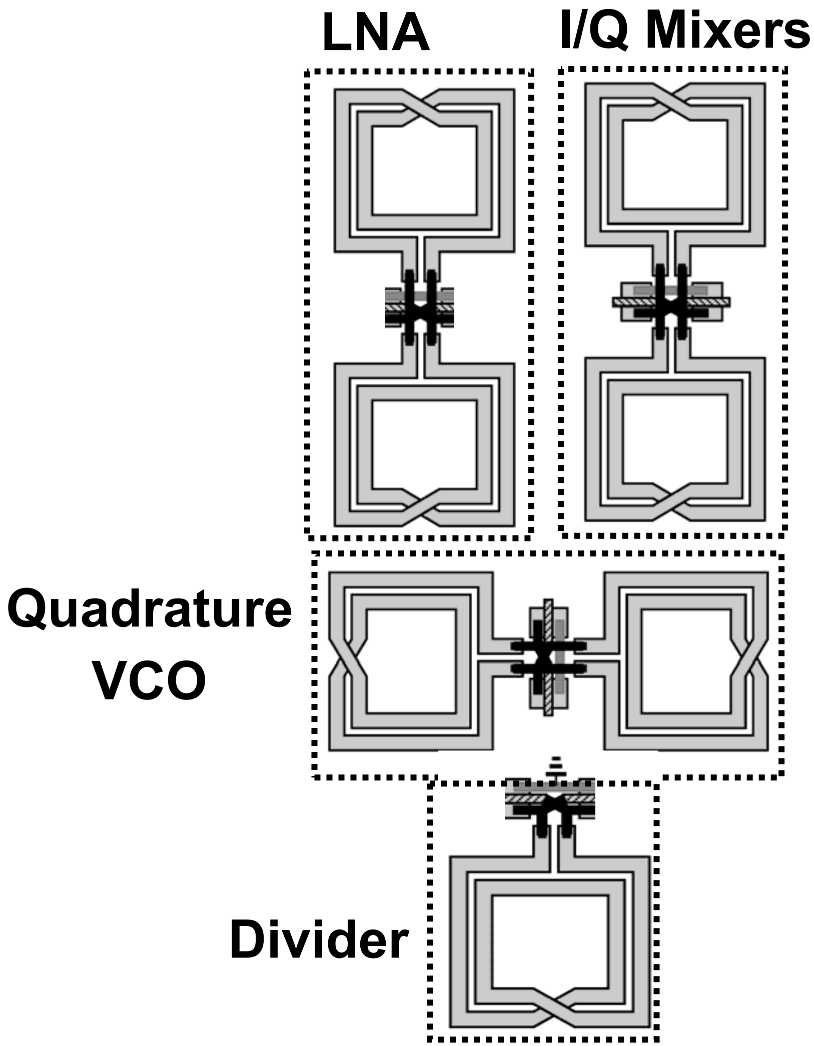
A Few Words for the RF-Challenged



Architecture-Level Challenges

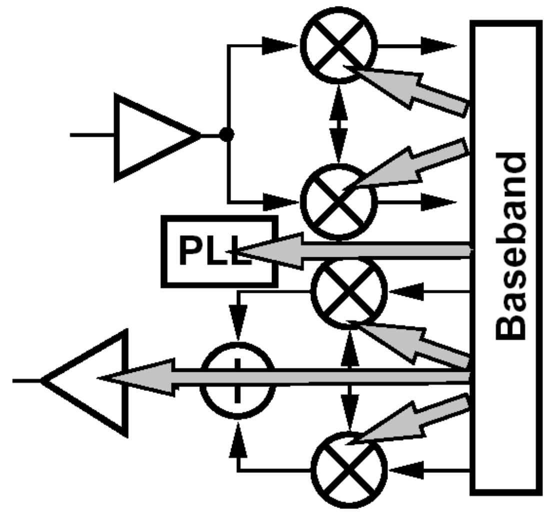
- LO (I/Q) Generation
- LO Division
- LO Distribution

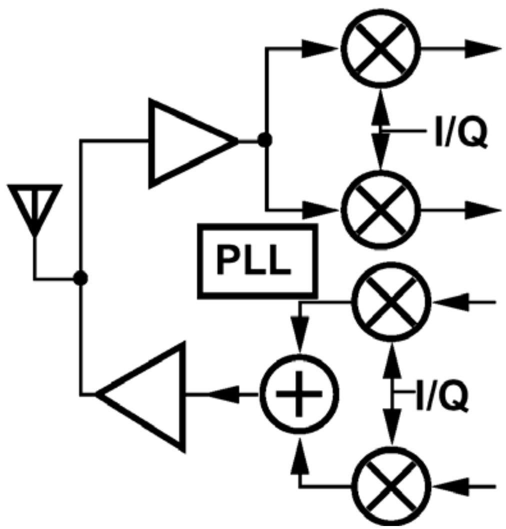




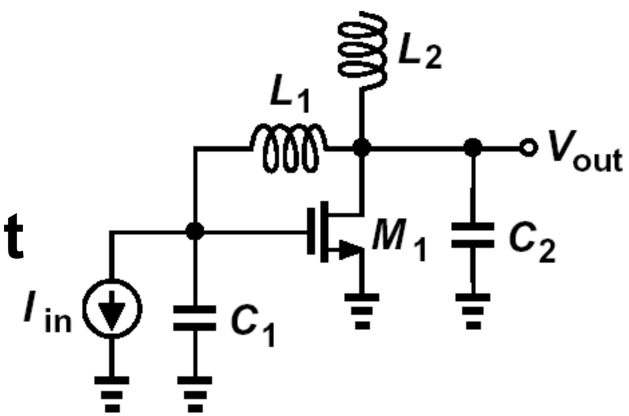
Innovation at All Levels

System



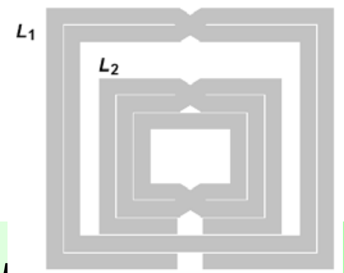


Architecture

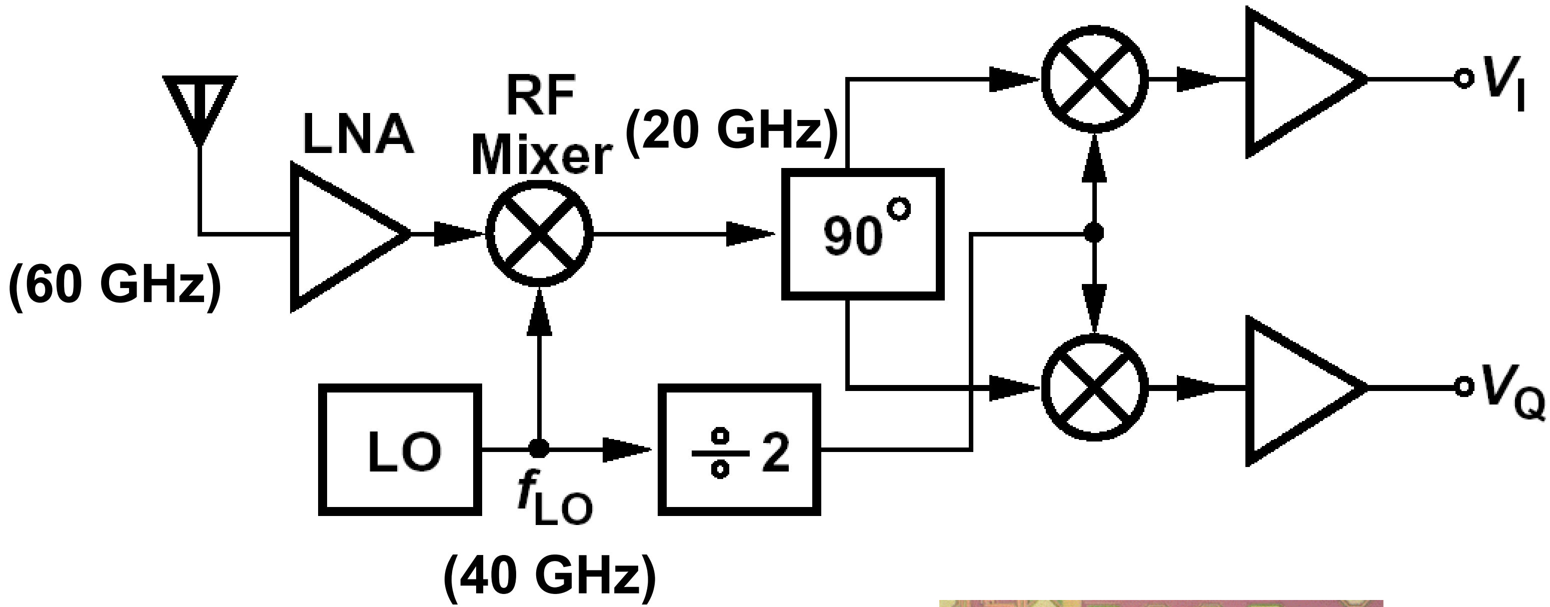


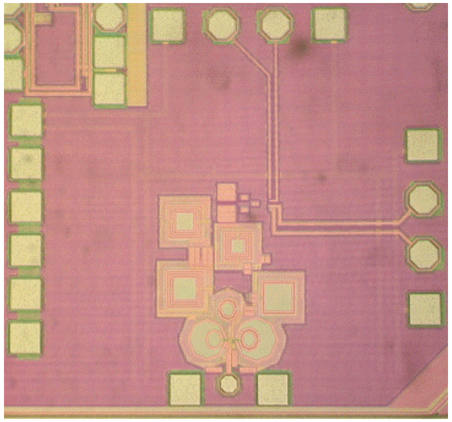
Circuit

Device



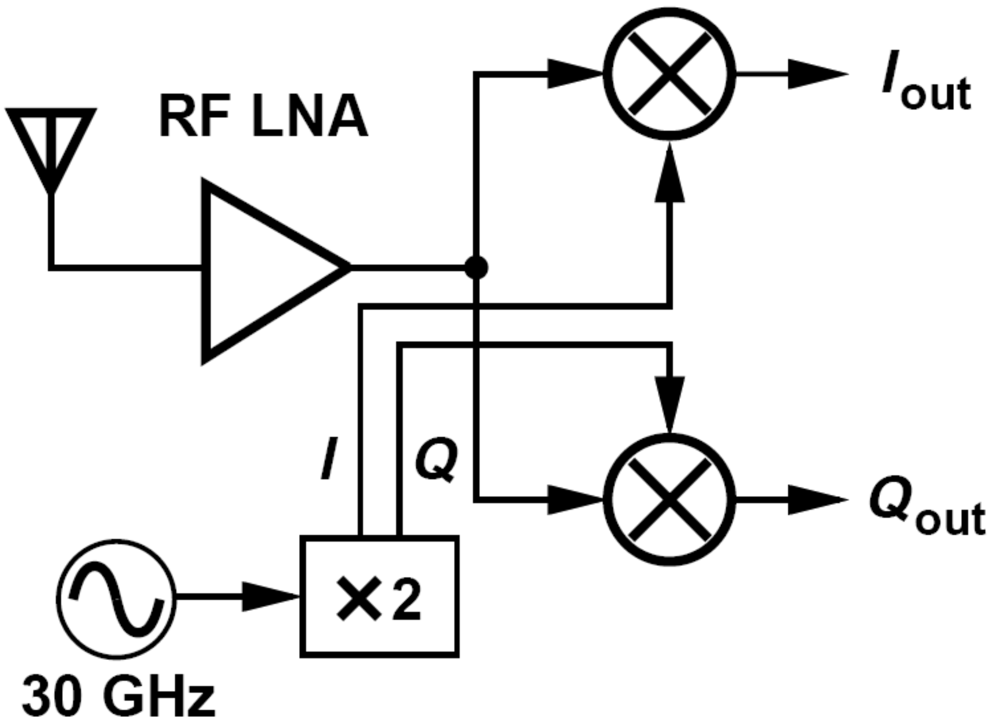
Our Second-Generation 60-GHz RX





[B. Razavi, ISSCC 07]

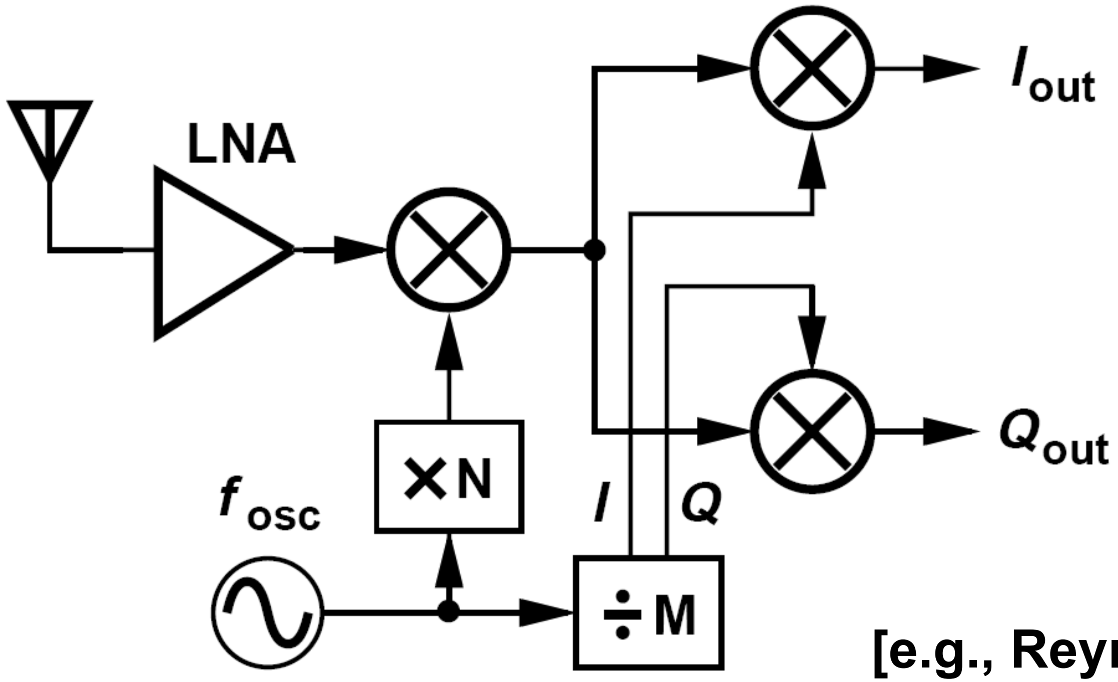
Direct-Conversion RX with 30-GHz LO?



- **Quadrature generation is difficult.**
- **Distribution is difficult.**

→Need "synthesizer-friendly" transceivers.

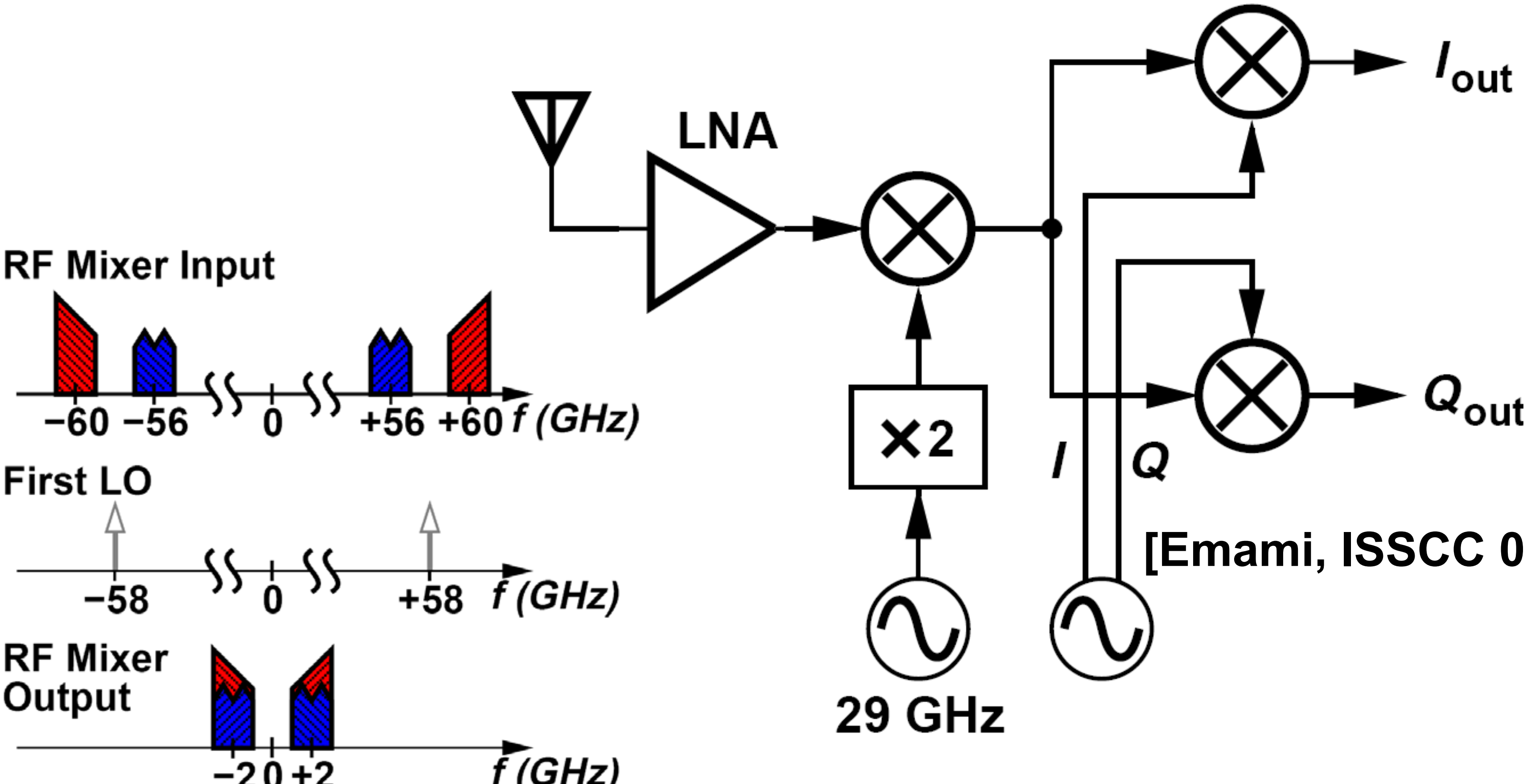
Heterodyne Receiver



[e.g., Reynolds, JSSC, Dec 06]

- Multiplier has high loss and needs its own inductor.

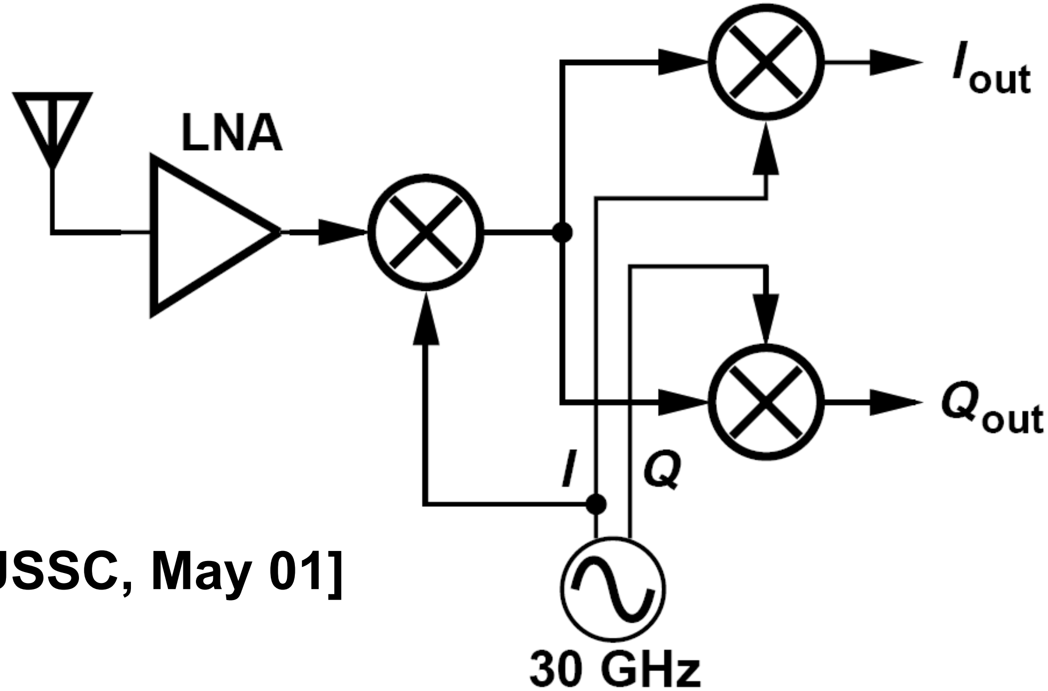
Problem of Low-IF Heterodyne



[Emami, ISSCC 07]

- Image of the first mixer is in the band.
- Receiver NF is increased by ~3 dB.

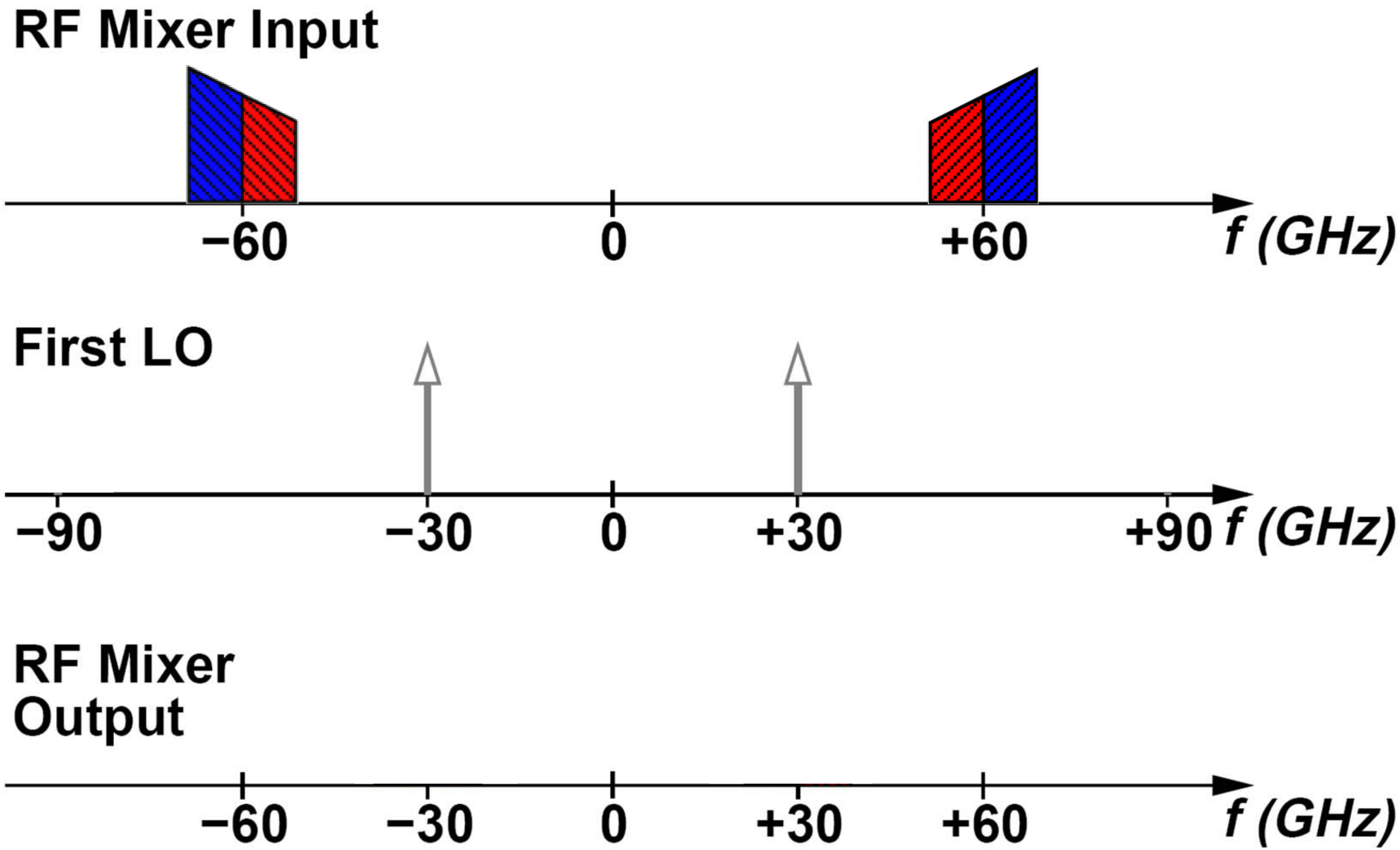
Example of Synthesizer-Friendly Receiver



[Razavi, JSSC, May 01]

- No extra divider/multiplier needed.
- Image is at DC.
- But,
  - Third harmonic of LO causes corruption.
  - LO-IF feedthrough may desensitize the IF mixers.
  - 1/f noise is upconverted in RF mixer.

Problem of LO Third Harmonic



Analysis

$$x_{RF}(t) = \Re\left[x_{BB}(t)e^{+j2\pi f_{RF}t}\right]$$

$$LO = \cos\omega_{LO}t + \alpha\cos 3\omega_{LO}t \quad \alpha \approx 1/3$$

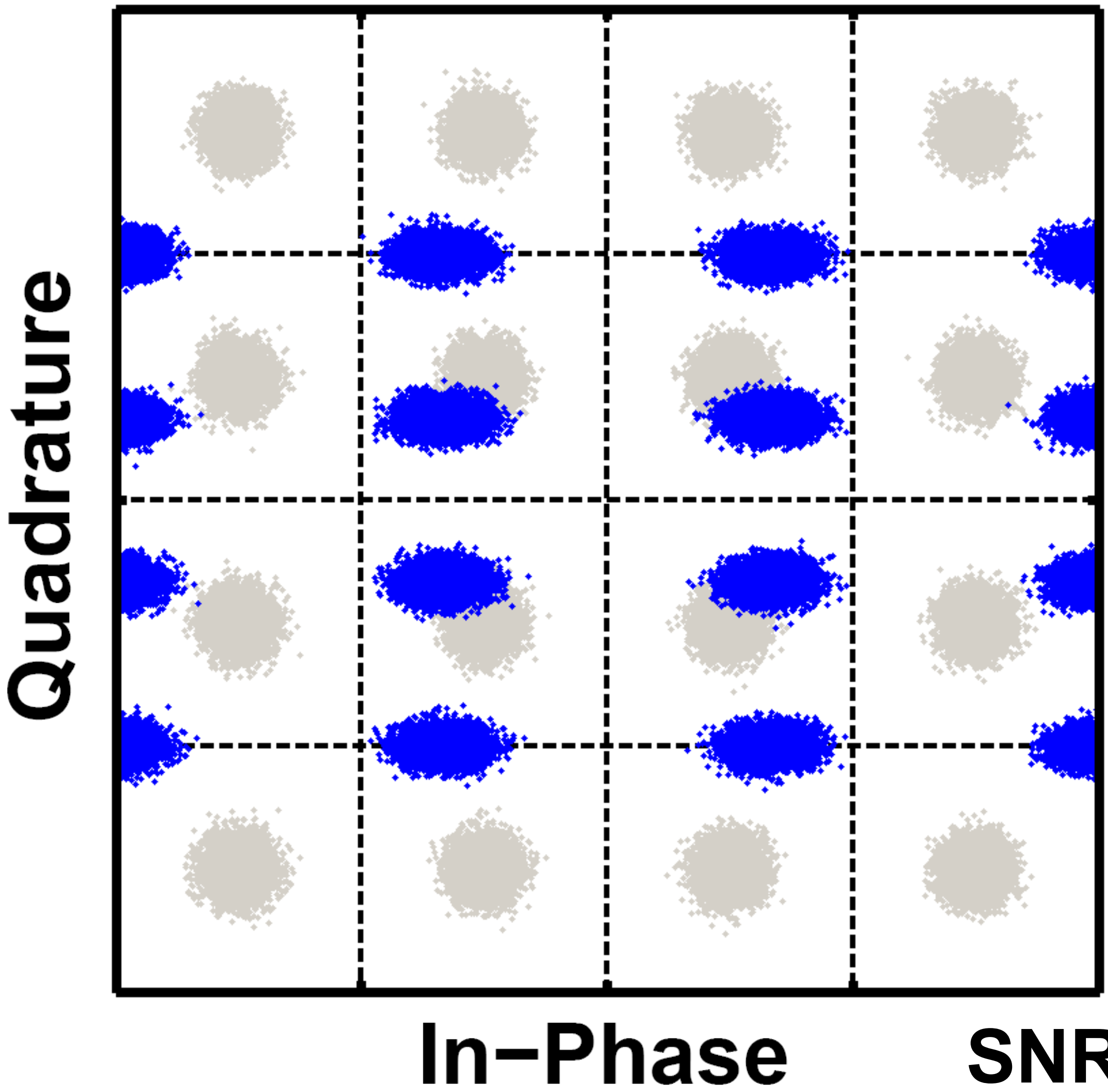
$$x_{IF}(t) = \Re\left[\frac{x_{BB}(t) + \alpha\, x_{BB}^{*}(t)}{2} e^{+j2\pi f_{IF}t}\right]$$

$$x_{out}(t) = k\left[x_{BB}(t) + \alpha\, x_{BB}^{*}(t)\right]$$

$x_{BB}(t)$ **: wanted signal** $\mathscr{F}\left\{x^{*}(t)\right\} = X^{*}(-f)$

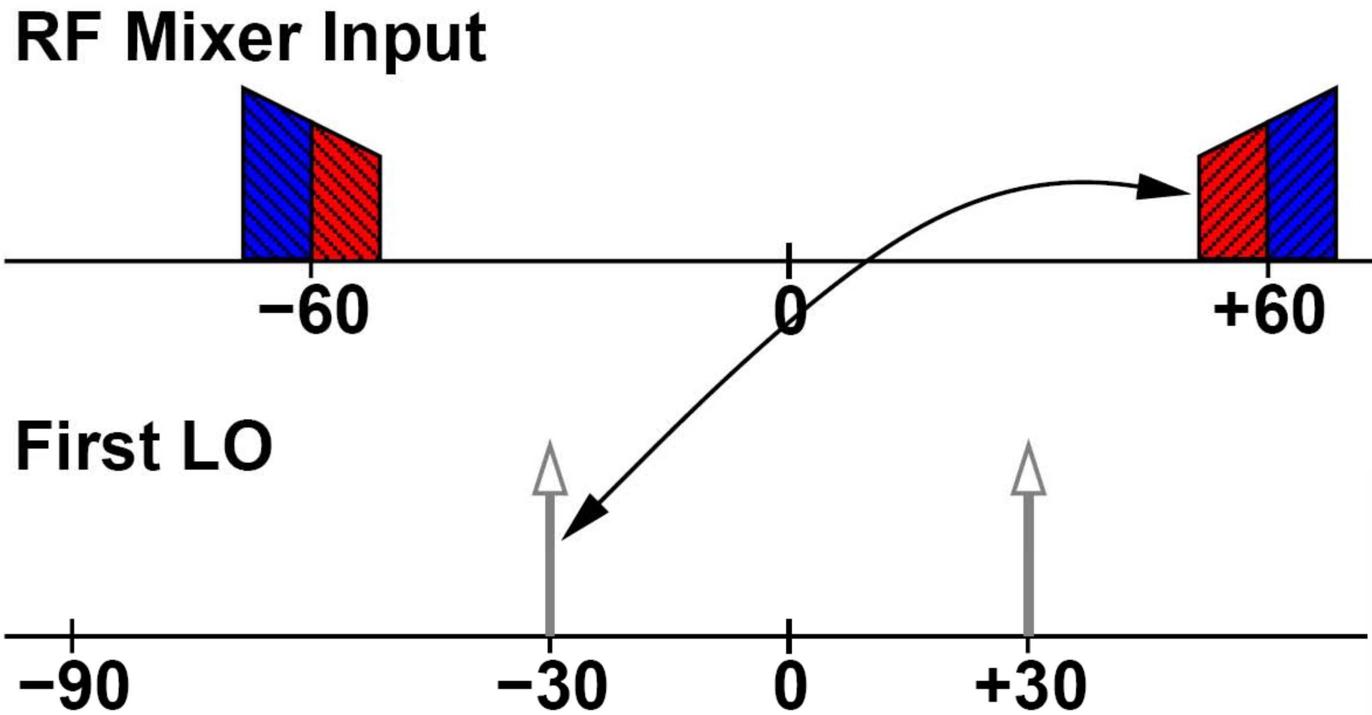
$x^{*}_{BB}(t)$**: mirrored replica of the signal**

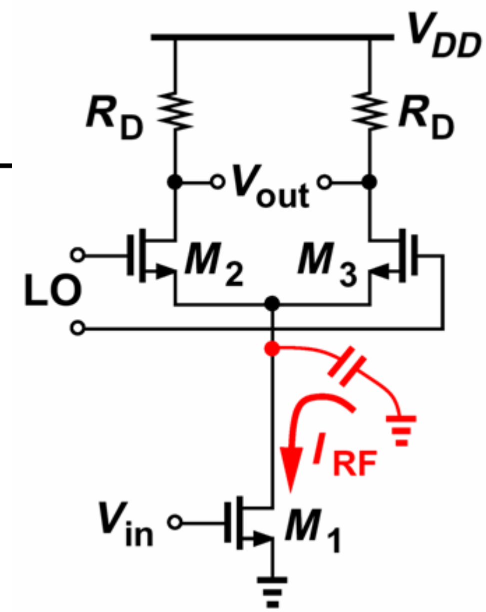
16-QAM Constellation



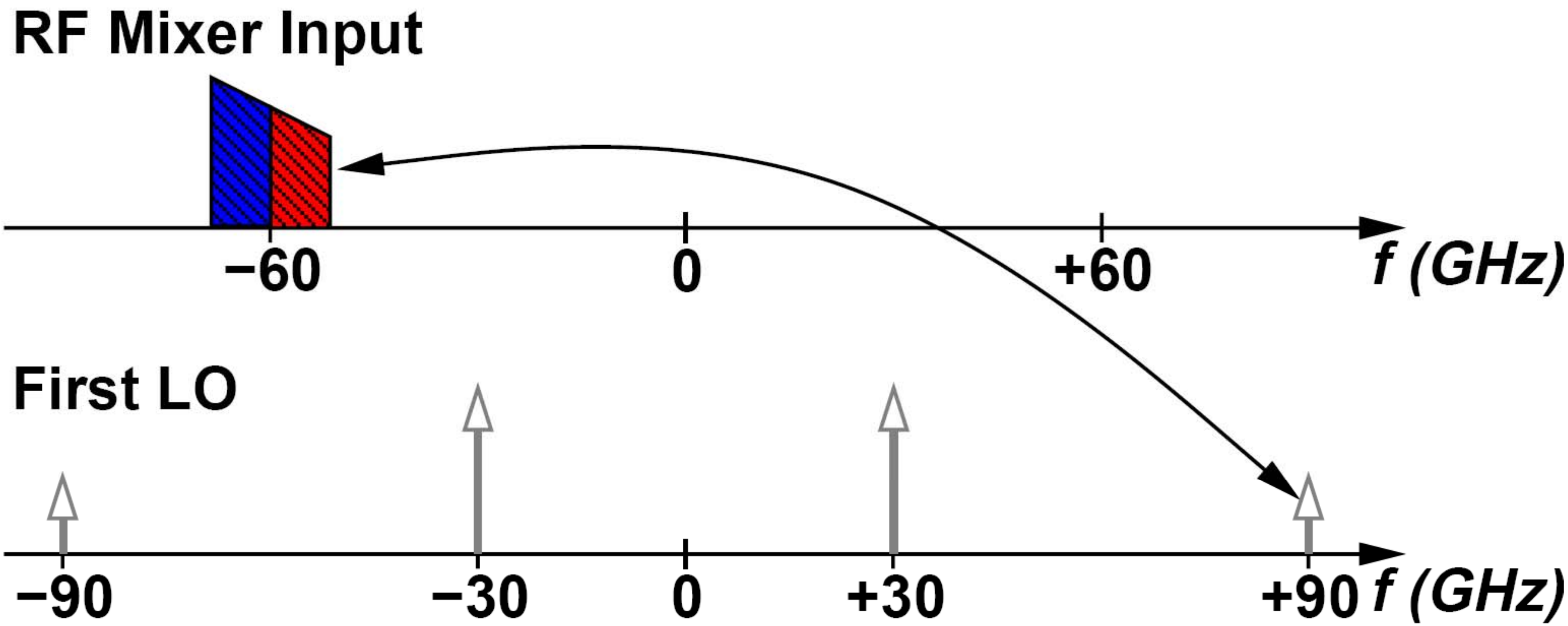
SNR = 25 dB

Linearize LO Port?

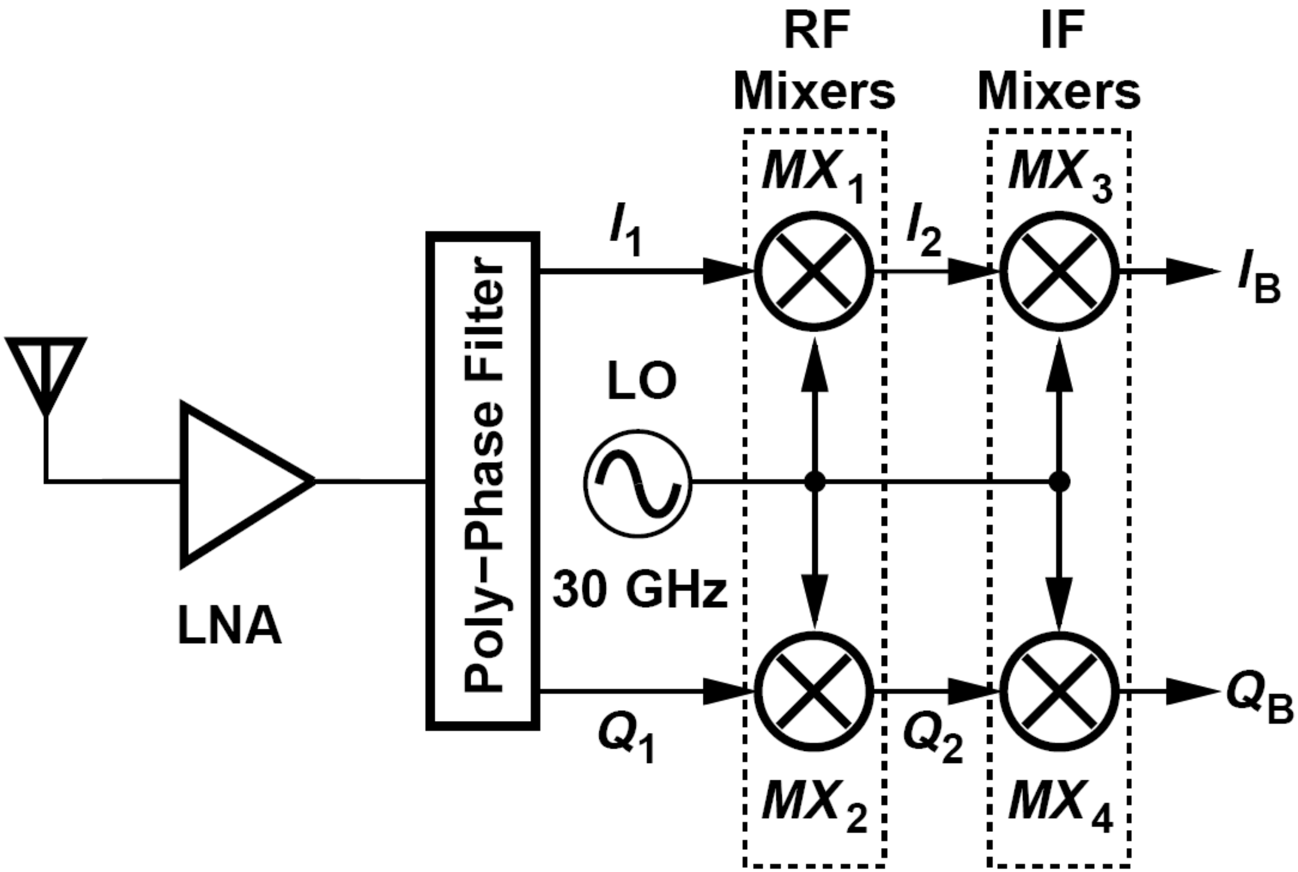




Alternative Solution

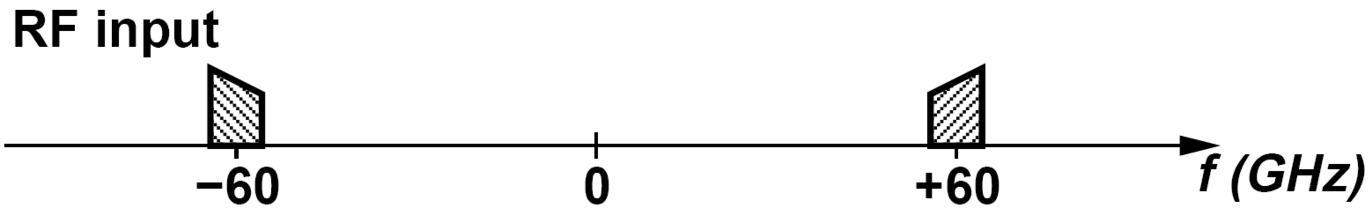


Proposed Receiver Architecture

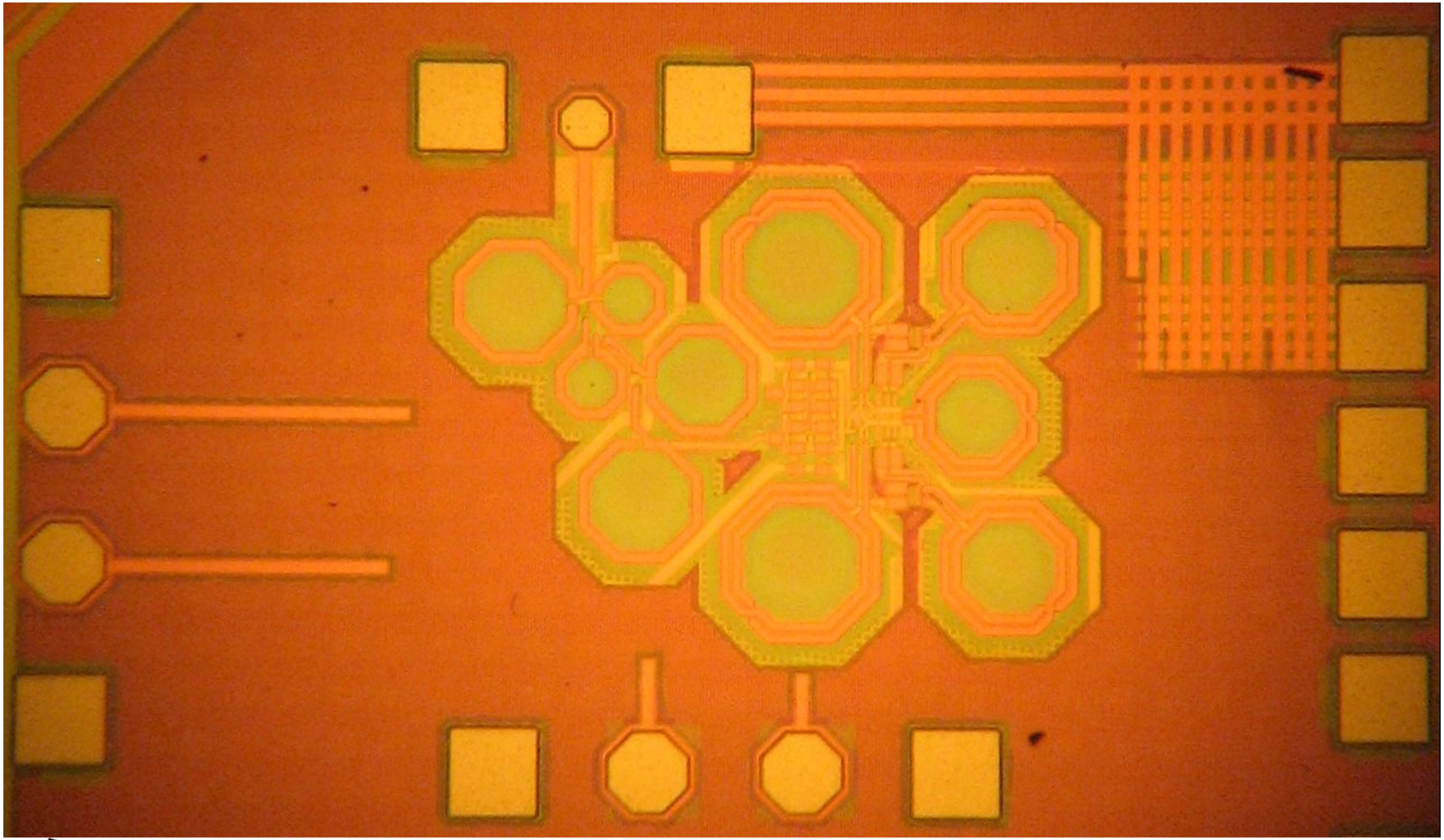


- **Lowest possible LO frequency (without multiplication).**
- **No quadrature LO phases required.**

Receiver Spectra



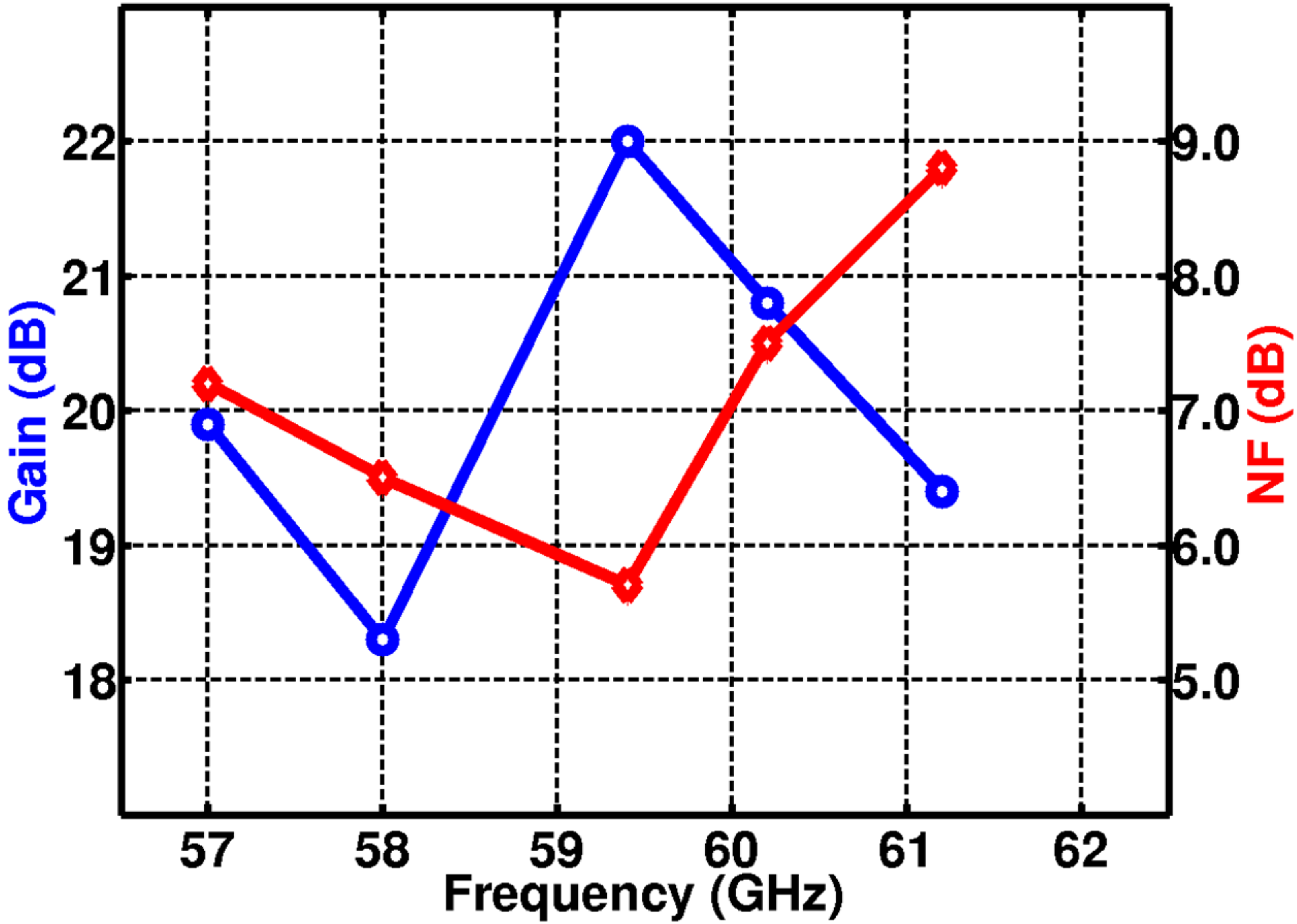
Die Photograph



Fabricated in TSMC's 90-nm CMOS technology.

Active area: 500 μm x 370 μm

Measured NF and Gain



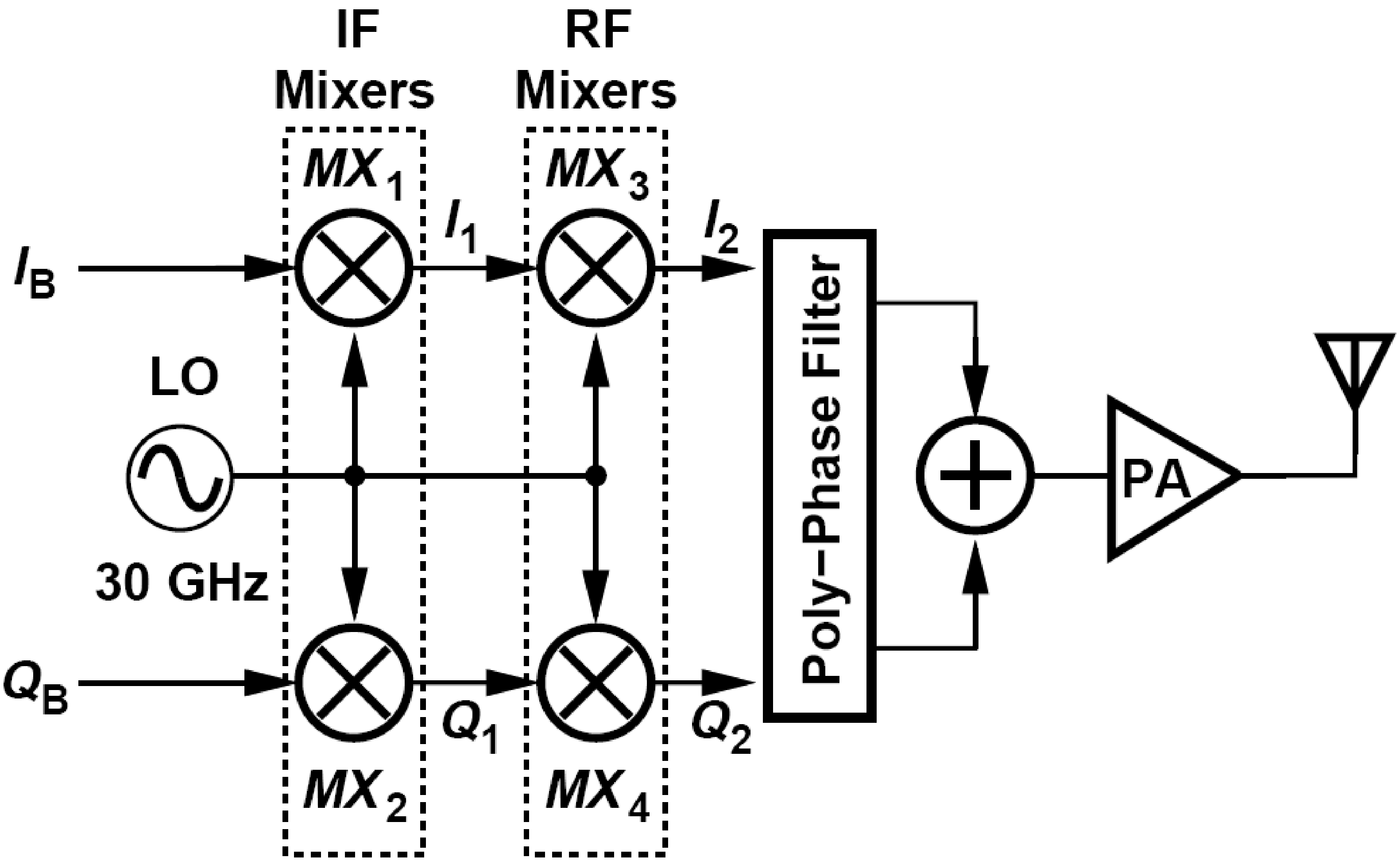
Comparison

	Receiver in [3]	Receiver in [1]	This work
Noise Figure (dB)	10.4-11	6.9-8.3	5.7-8.8
Gain (dB)	9.5-12	26-31.5	18.3-22
P_{1dB} (dBm)	-15.8	-25.5	-27.5
LO Leakage to Input (dBm)	N/A	-47	-65
I/Q Mismatch	N/A	6.5°/ 1.5dB	2.1°/ 1.1dB
LO Phase Noise (dBc/Hz @ 1-MHz offset)	-86	-95	-87
Power Dissipation (mW)	77	80	36
LNA			9
Mixers			23
Oscillator			4
Supply Voltage (V)	1.2	1.8	1.2
CMOS Technology	0.13-μm	90-nm	90-nm

[1] B. Razavi, ISSCC ‘07

[3] S. Emami et al, ISSCC ‘07

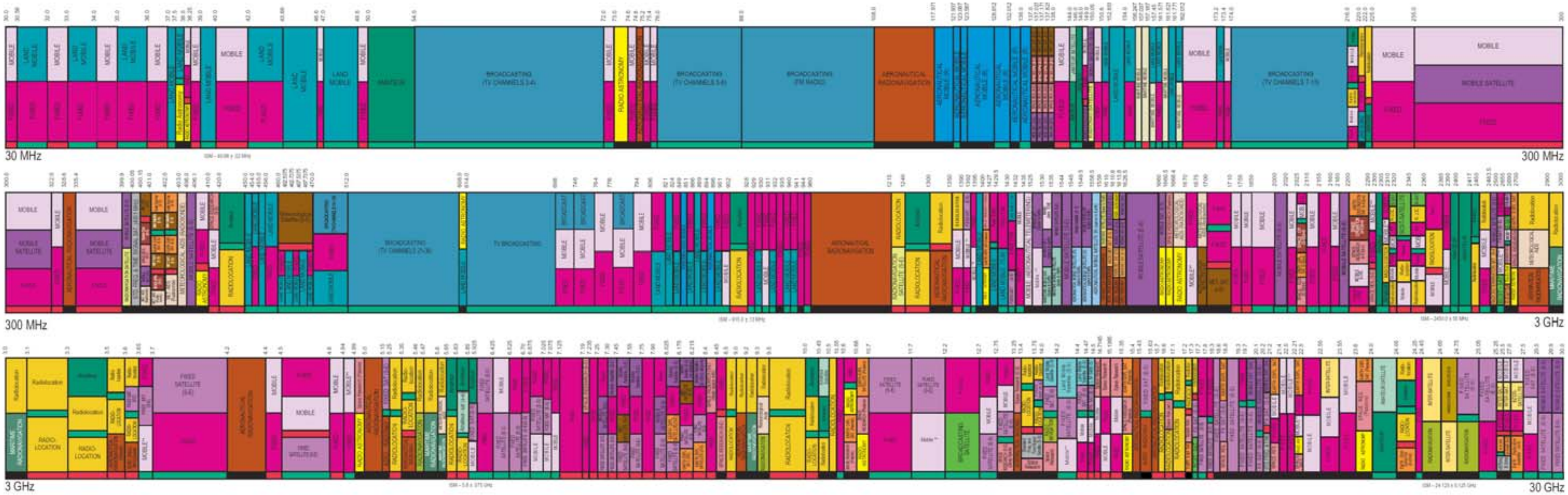
Transmitter Architecture



- **Does not require quadrature LO**

Cognitive Radio

Detect and use unoccupied channels.

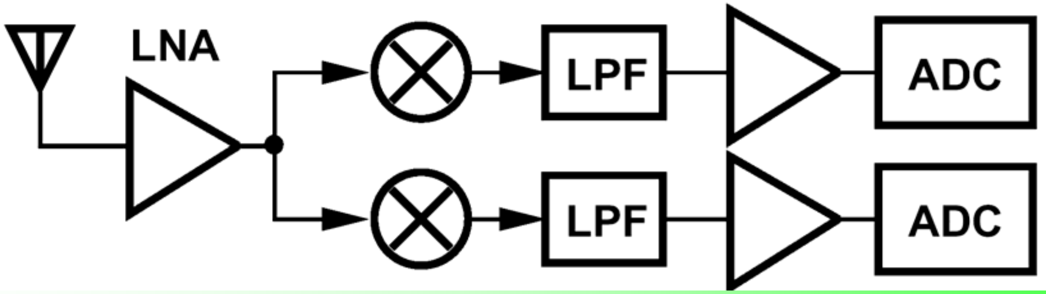


RF/Analog PHY Design Issues

- Spectrum Sensing
- RX Path
- TX Path
- Frequency Synthesis

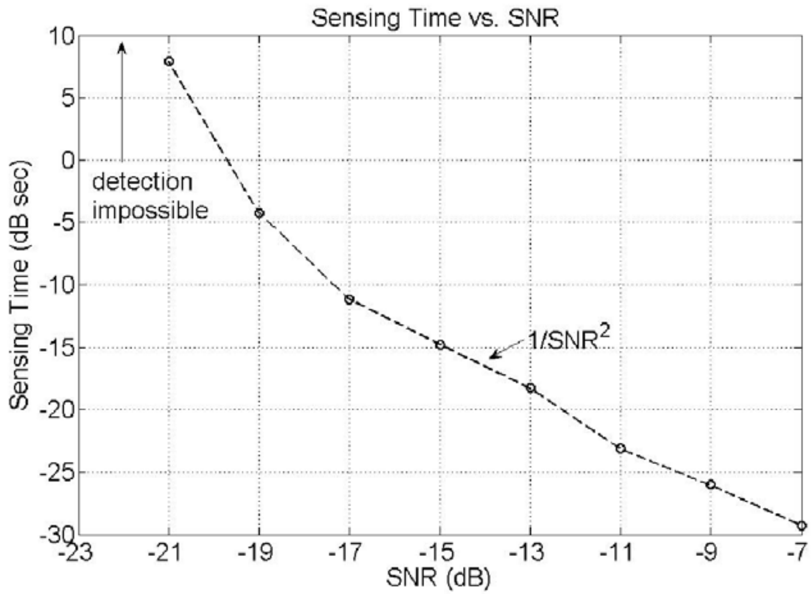
Spectrum Sensing (I)

- Three Techniques:
  - Energy Detection
  - Pilot Detection
  - Signal Feature Detection
- Need to measure SNR~ -20 dB →
  - Accurate calibration of RX NF (i.e., need a tone with accurate amplitude)
  - Need enough gain to raise RX noise to well above 1 LSB of ADC



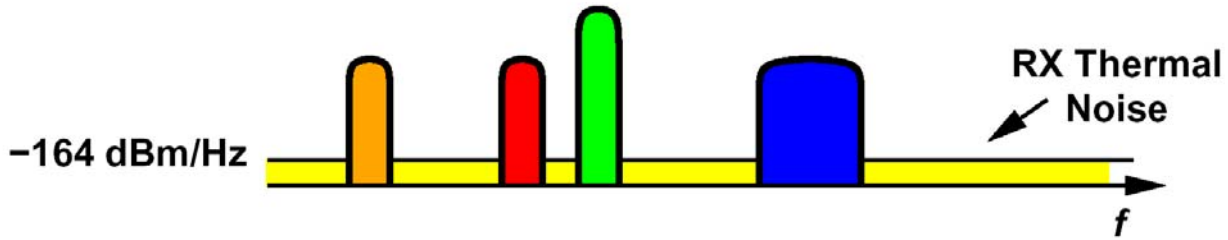
Spectrum Sensing (II)

- **Channel-by-Channel Sensing**
  - Relaxed ADC design (~3 bits)
  - Takes forever.
    (e.g., 4-MHz QPSK channel:
    30 ms for SNR=-17 dB)
  - May not know the center
    or bandwidth of channel.



[Cabric, PhD Diss., UCB]

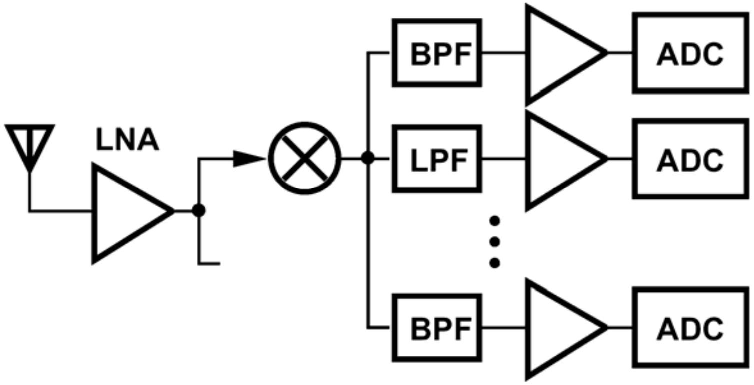
- **Block Downconversion Sensing**
  - Proportionally faster
  - But ADC BW and resolution
    much tougher



Spectrum Sensing (III)

- **Two-Step Sensing:**

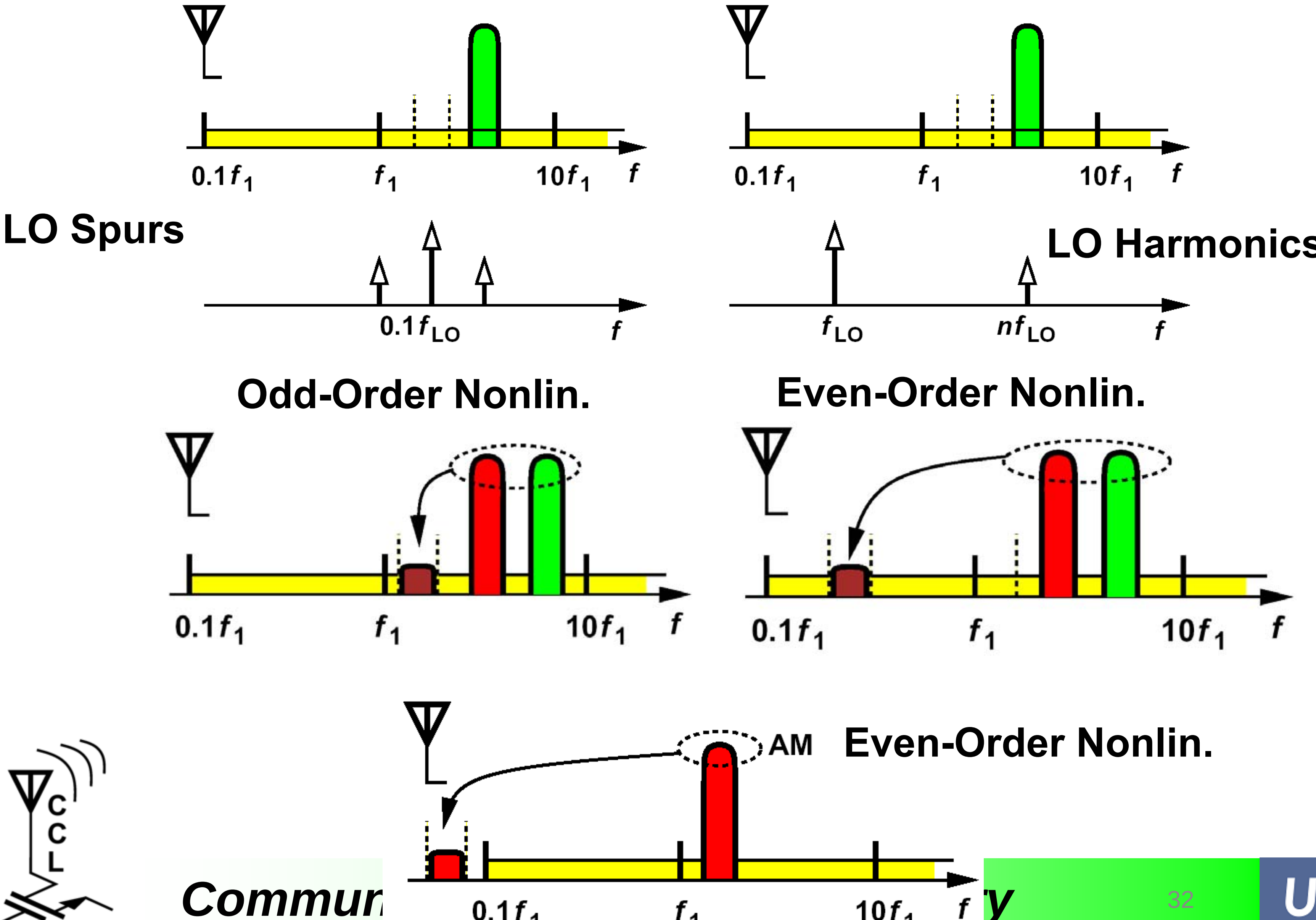
  1. **ADC takes a snapshot of a block of channels and determines "potentially-unoccupied" channels.**
  2. **Baseband filters "zoom in" onto those channels and multiple ADCs digitize them.**



- Given certain blocker levels, what ADC resolution suffices for the first step?

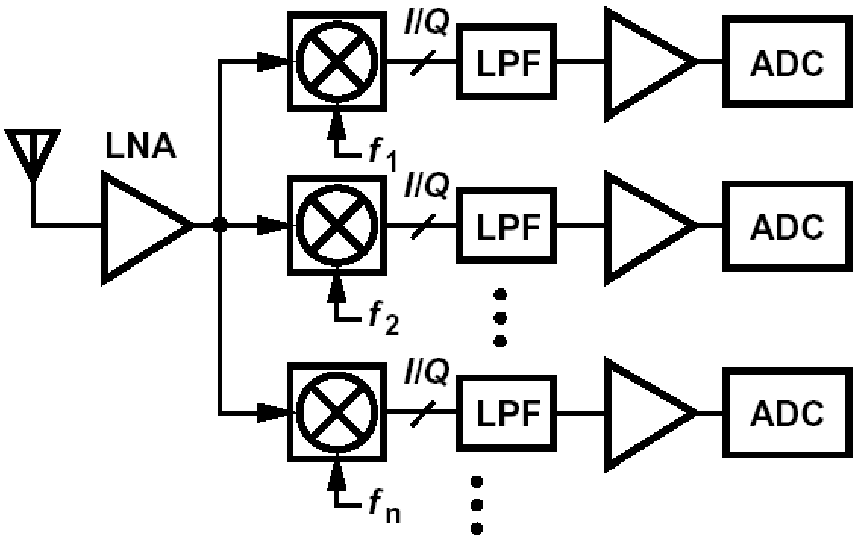
- What criteria should be used to determine "potentially-unoccupied" channels?

Effect of Spurs, Harmonics, and Other Blemishes



RX Path

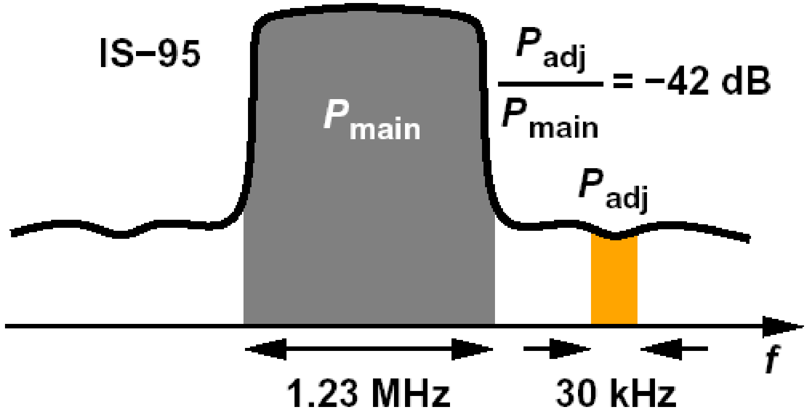
- Broadband gain and input matching
  - Difficult to switch different circuits in and out at the input.
- Low noise – especially flicker noise for 20-50 MHz
- High IP3 and IP2
- Multiple concurrent downconversions to speed up spectrum sensing:



Concurrent reception of multiple channels?

TX Path

- **Broadband upconversion, PA, and matching**
- **Low adjacent-channel power**



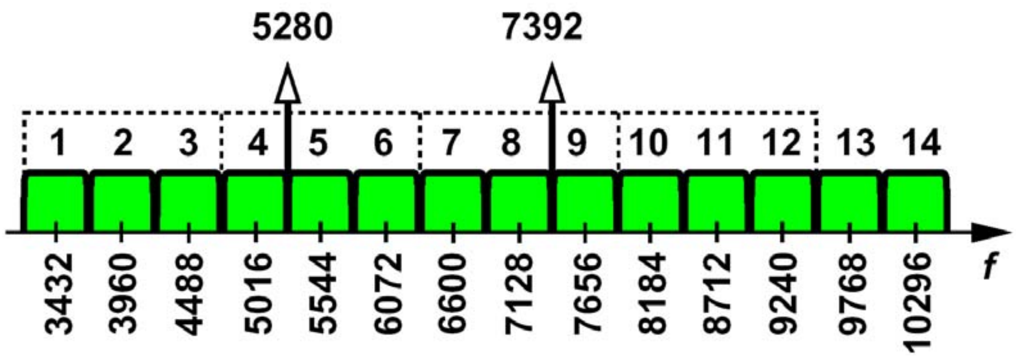
→ -26 dBc

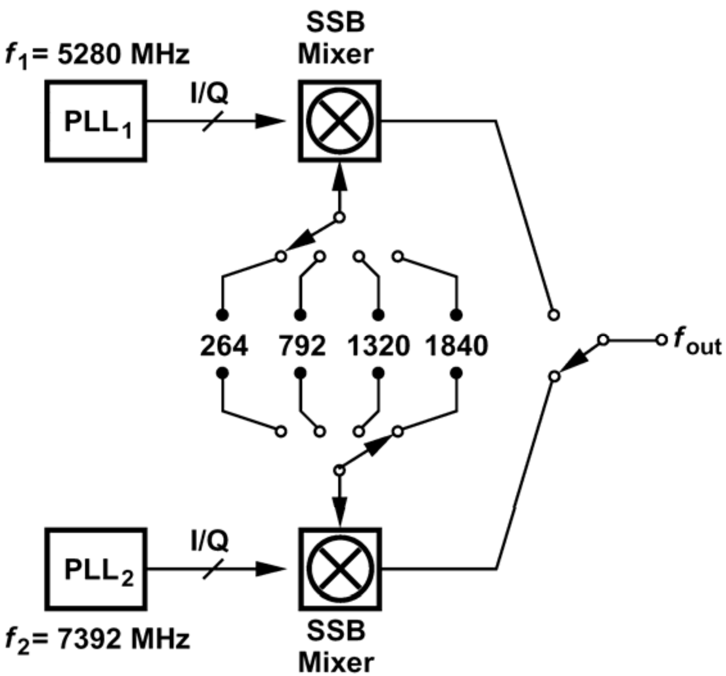
- **Concurrent Transmission and Sensing?**
- **Concurrent Transmission in multiple channels?**

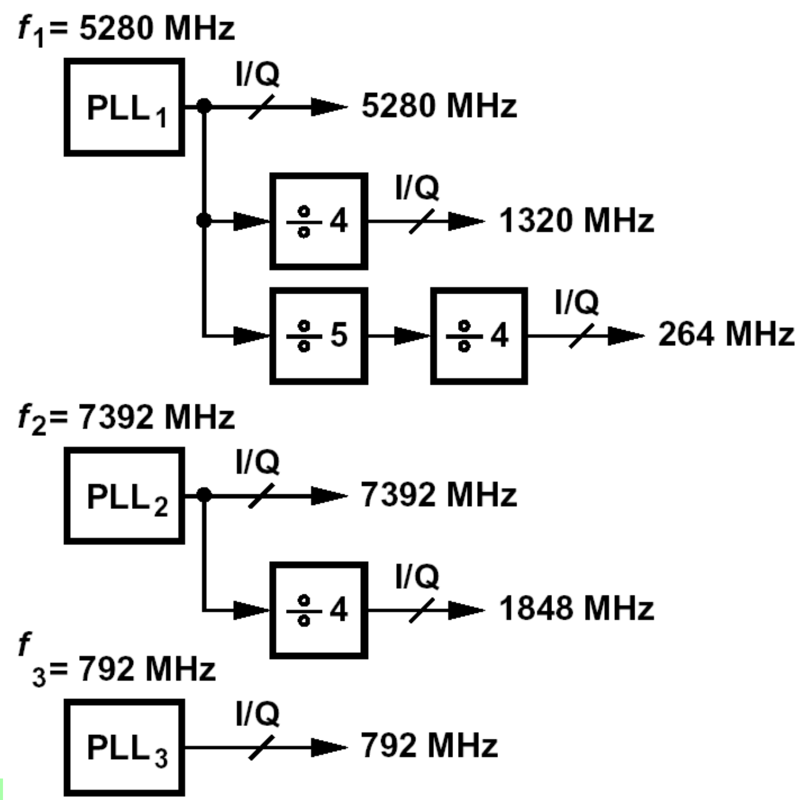
Frequency Synthesis: 2.5 Decades

- **LC VCO Tuning Range < +/- 10%**
- **If a frequency is divided by an odd number, it must then be divided by 4 to generate quadrature phases.**
- **Single-sideband mixing probably out of the question**
- **How many VCOs does it take to cover one decade?**

UWB Example

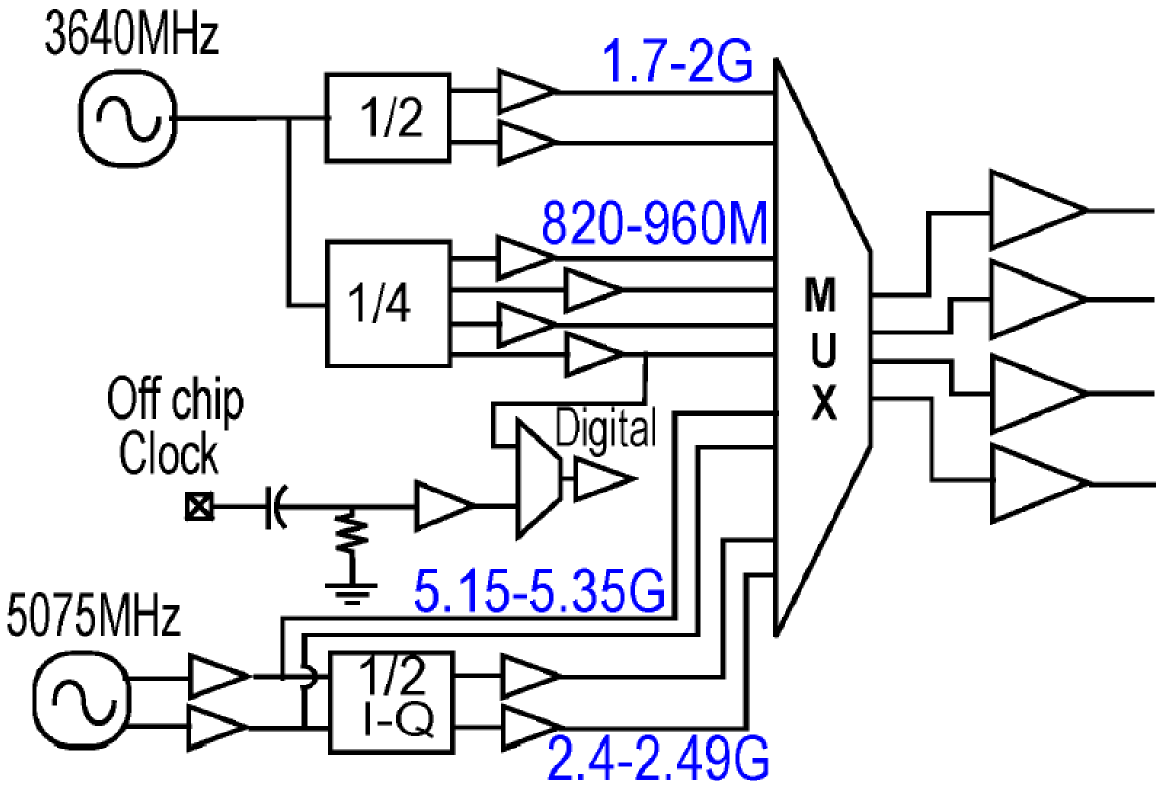






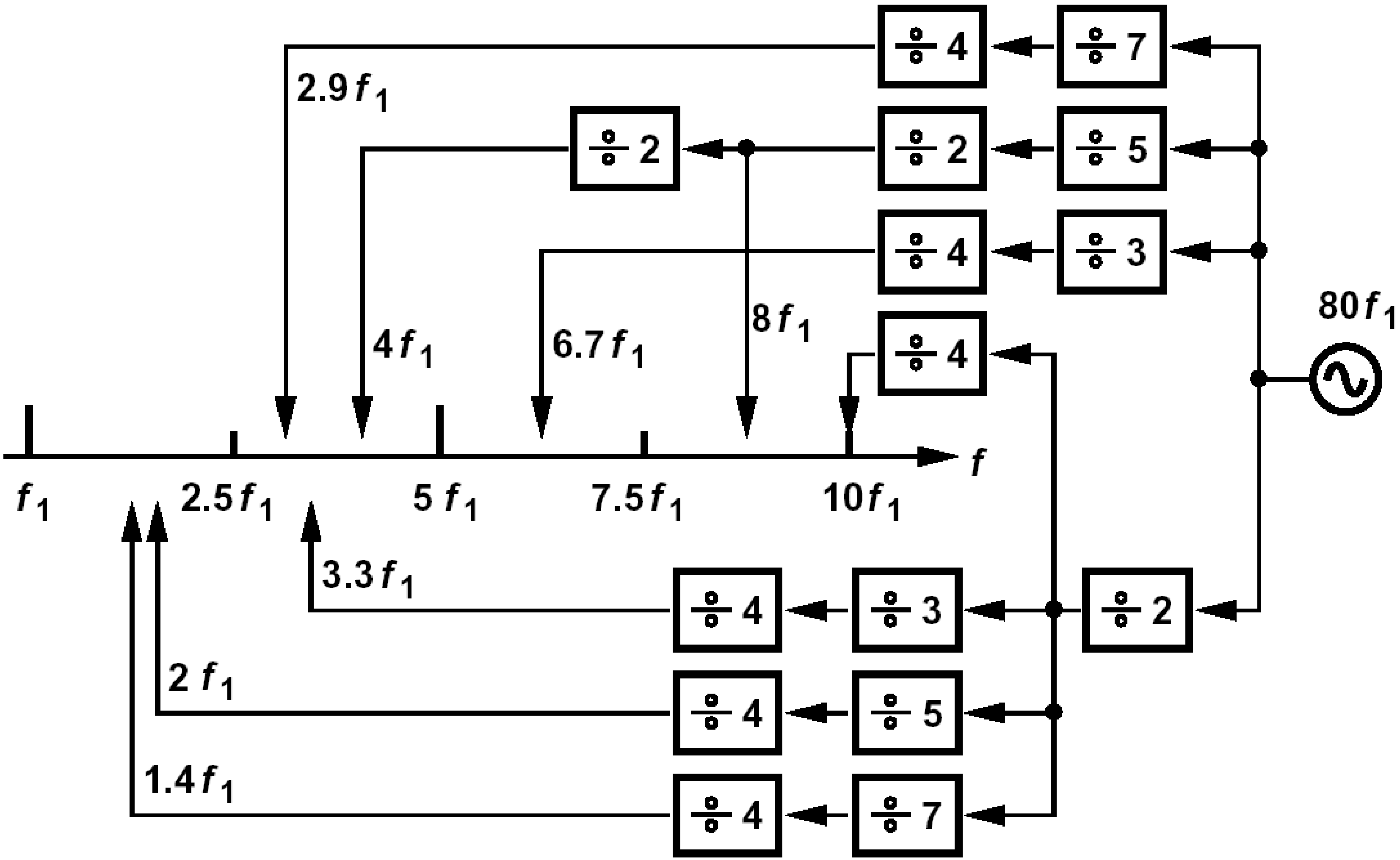
[Razavi et al, CICC05]

SDR Example



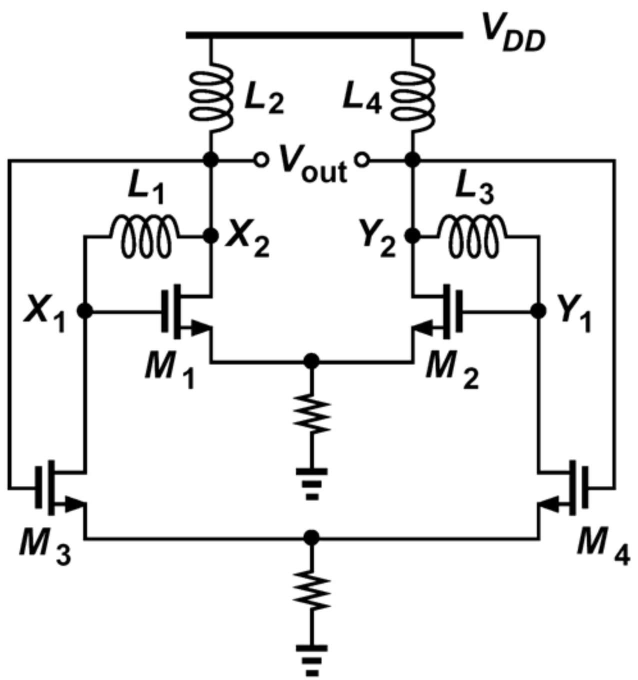
[Bagheri et al, ISSCC06]

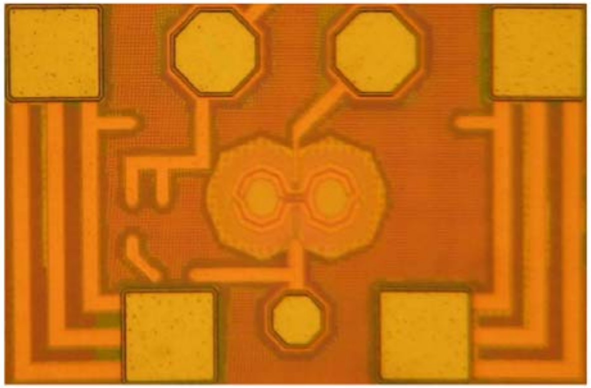
How to Cover One Decade?

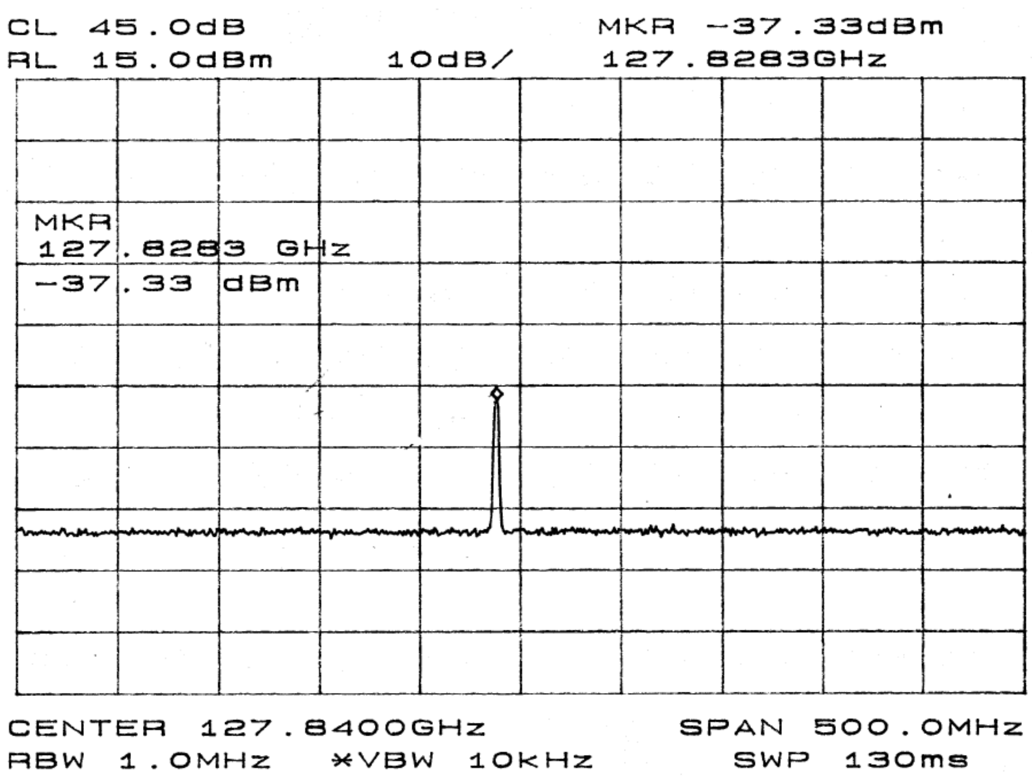


Millimeter Waves to the Rescue

128-GHz Osc. in 90-nm CMOS



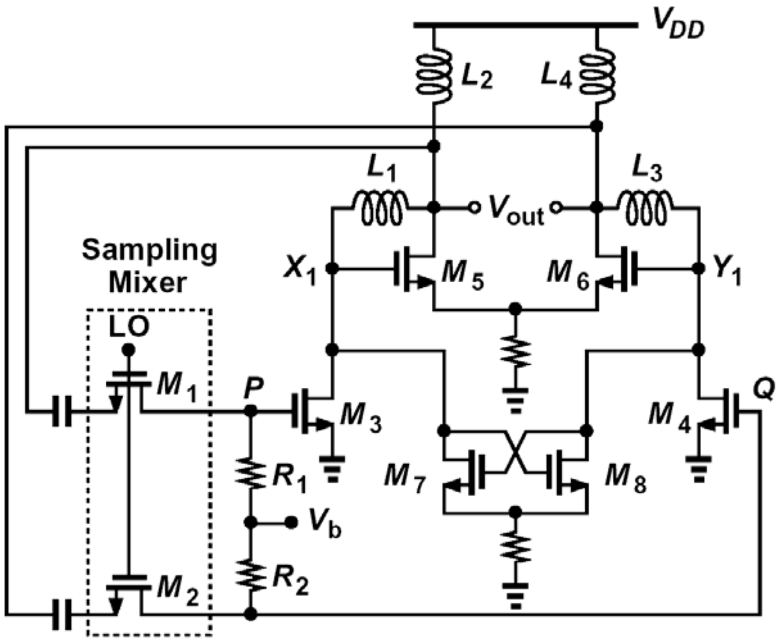


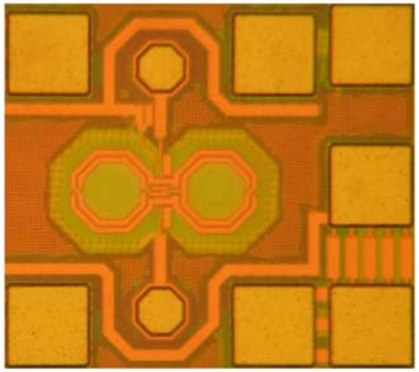


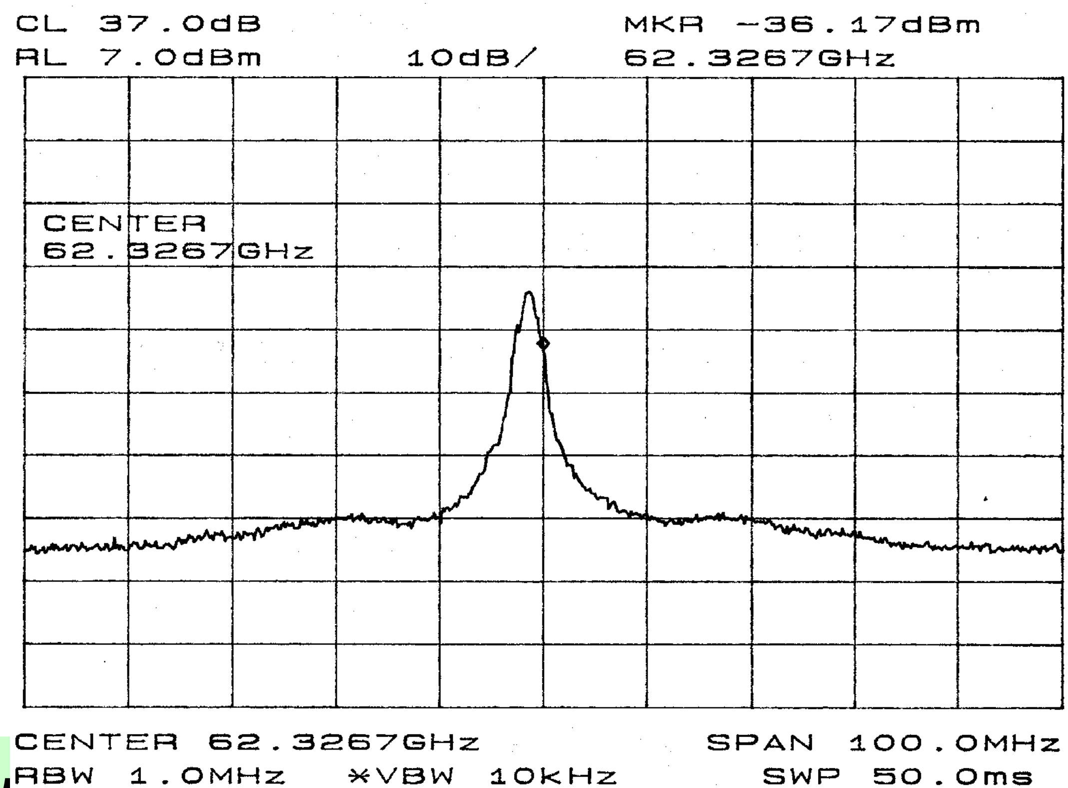
[Razavi, JSSC, Sept. 08]

Millimeter Waves to the Rescue

125-GHz Divider in 90-nm CMOS

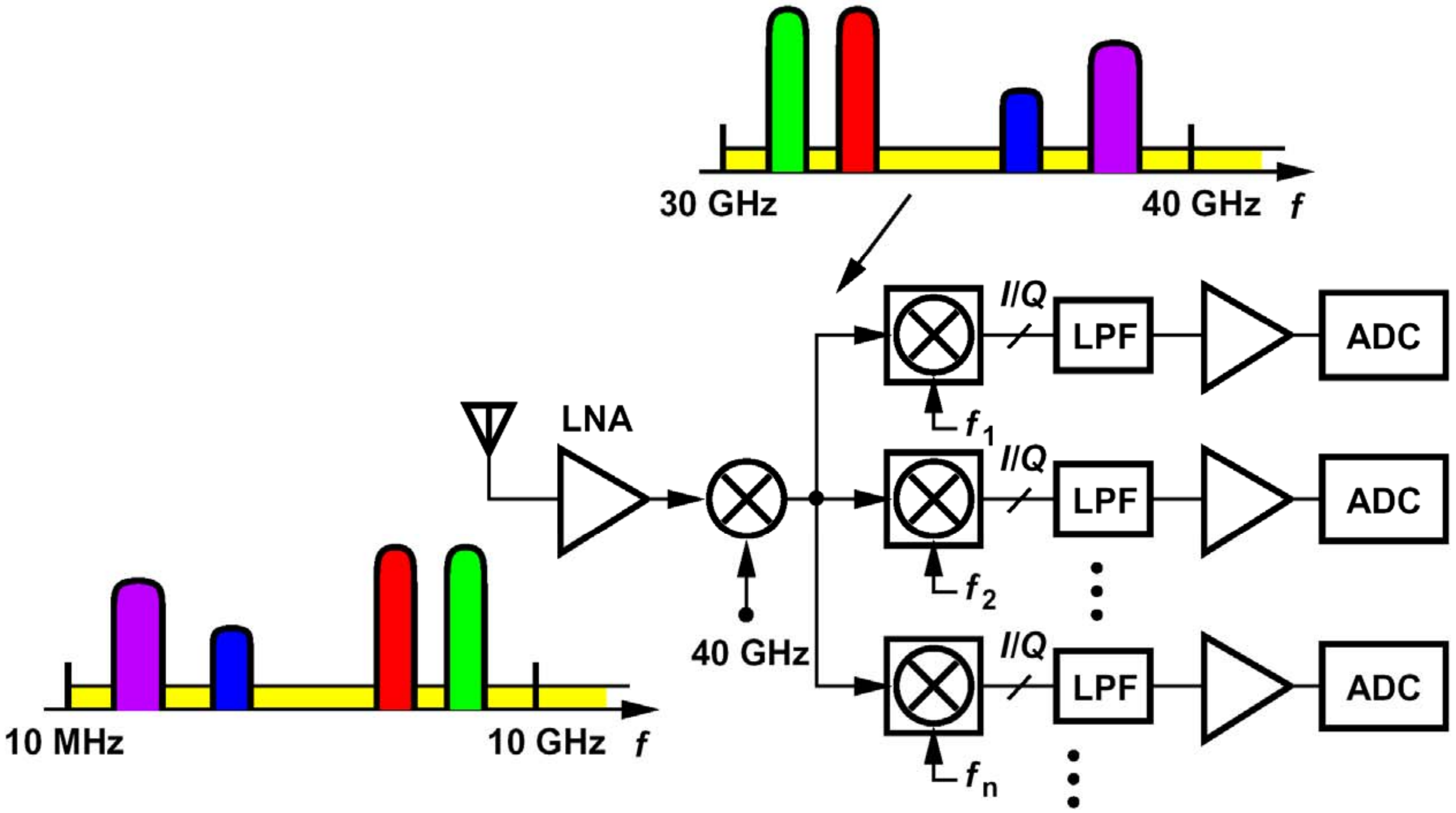






[Razavi, JSSC, Sept. 08]

Alternative Solution



Conclusion

- **Millimeter-wave and ognitive radios pose new challenges in RF and analog design – thereby keeping us employed.**
- **Cross-fertilization of concepts from UWB and mm-waves can greatly benefit CRE design.**
- **Many issues need to be studied and quantified:**
  - Baseband ADC Requirements
  - NF Calibration
  - Coverage of 2-3 Frequency Decades
  - Broadband Gain, Matching, PAs, etc.