Evolution of the Software-Defined Radio (SDR) Receiver

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The Need

Quad-band GSM

GPRS

Wideband CDMA

EDGE

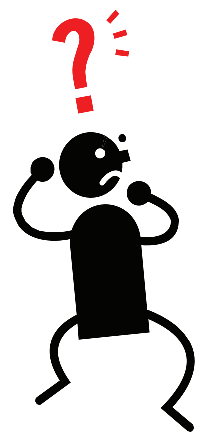
GPS

Bluetooth

802.11b ...

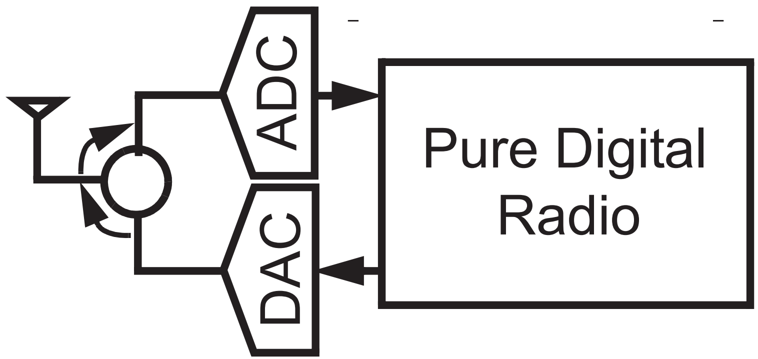
Cram down the funnel of functions

- Large number of independently developed radio boards, all squeezed into a small mobile device ...
- You see one antenna, there are actually 3 or 4 ...
- Next month there will be a new wireless application
- Where will this end??

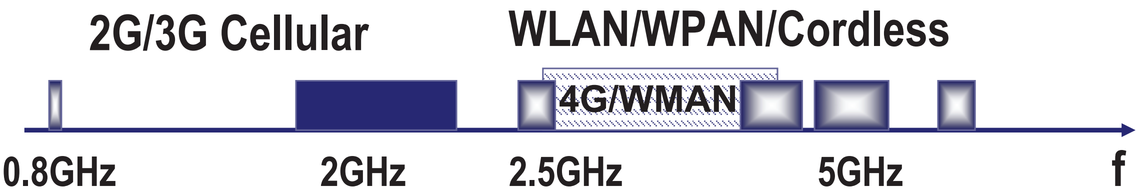


The Software Defined Radio

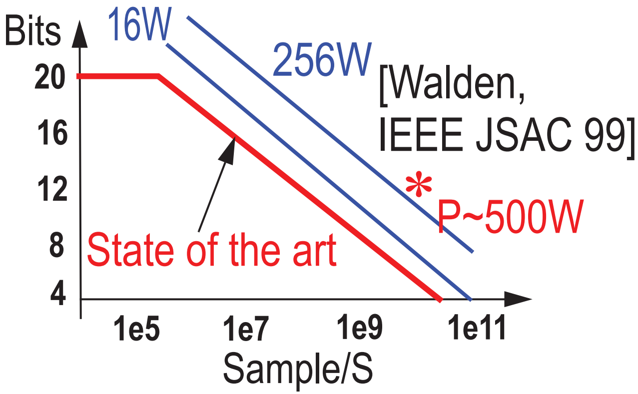
Mitola 1995



- Ultimate in flexibility!



- Needs 12b, 10 GS/s A/D Converter (ADC)



- Low power solution not in sight, Moore's law doesn't help

Goals for today's SDR Transceiver

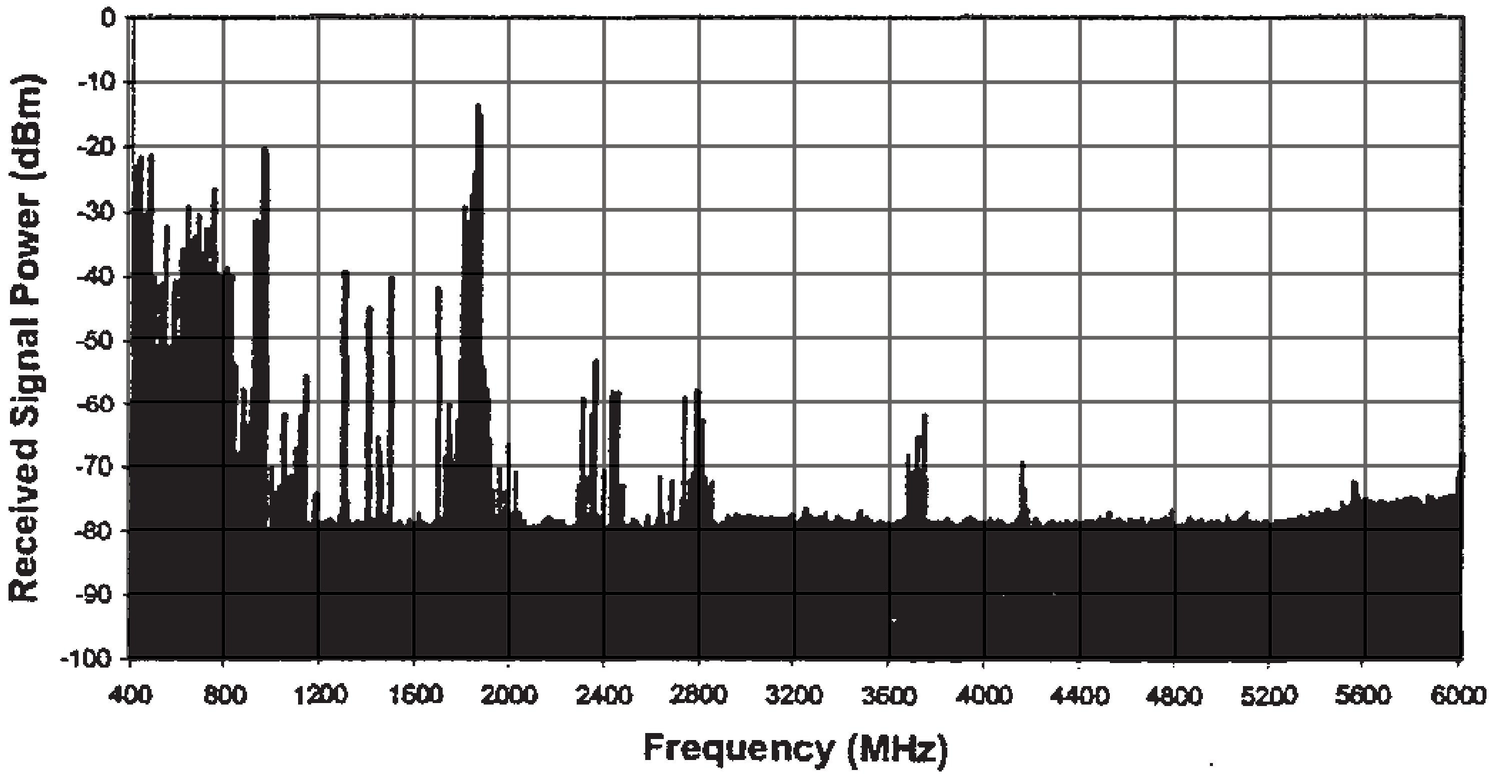
Table 1: RX frequency bands

Center Frequency Band [MHz]	Standard
460.4-467.6	2G,3G
488.8-496	2G,3G
869-894	2G-3G
925-960	2G-3G
1805-1880	2G-3G
1881-1897	2G-3G
1900-1920	3G
1930-1990	2G-3G
2010-2025	3G
2110-2170	3G
2170-2200	3G
2400-2484	ISM (11g/b, ..)
5150-5350	UNII (11a,cordless)
5725-5825	UNII (11a,cordless)

Table 1: TX frequency bands

Center Frequency Band [MHz]	Standard
450.4-457.6	2G,3G
478.8-486	2G,3G
824-849	2G-3G
894.1-915	2G-3G
1710-1785	2G-3G
1881-1897	2G-3G
1900-1920	3G
1850-1910	2G-3G
1920-1980	3G
1980-2010	3G
2010-2025	3G
2400-2484	ISM (11g/b, ..)
5150-5350	UNII (11a,cordless)
5725-5825	UNII (11a,cordless)

What does the spectrum look like actually?

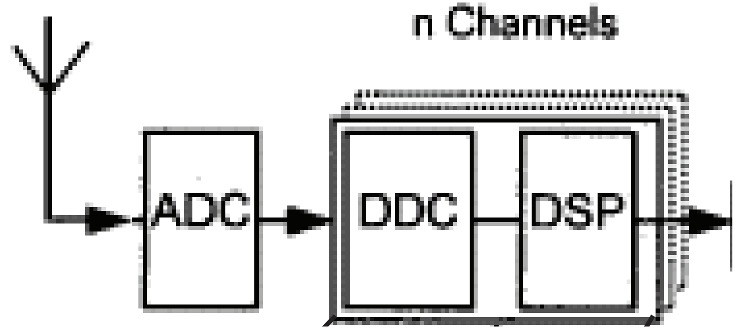


- Strong signals in only a few bands, and near base stations
- Worst-case blocker profiles are pessimistic

Watkins, Bristol U., 2001

What's wrong with this concept?

- Mitola's SDR can receive every band and channel concurrently!
- May be important for military, not necessary for civilian uses



Digital RX

Standard	Modulation Scheme	Channel BW (MHz)
GSM	GMSK	0.200
EDGE	8PSK	0.200
Bluetooth	GFSK	1
CDMA IS95	QPSK CDMA	1.25
WCDMA/ CDMA2000	QPSK/16QAM CDMA	1.25-5
802.11a/g	OFDM	20
802.11n	OFDM	10-20-40

Modified SDR

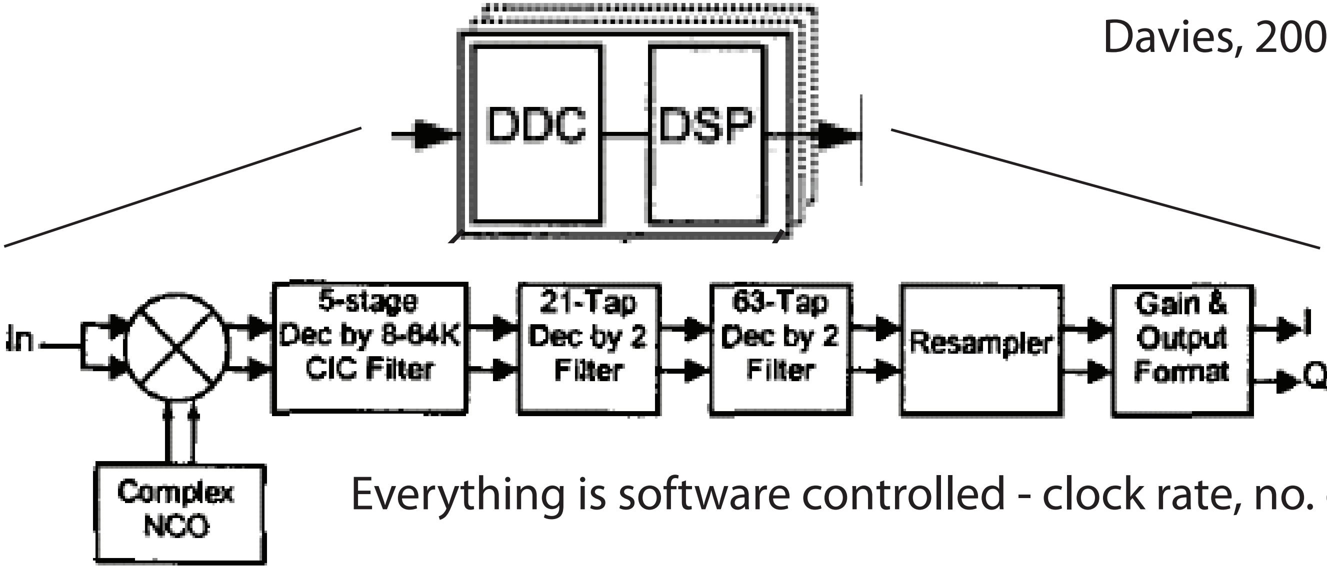
① Good enough to receive one channel at a time, but from **any band**, with **any channel bandwidth**, and **any modulation**

② Tunes channel of interest to zero IF

③ Wideband receiver (no RF preselect)

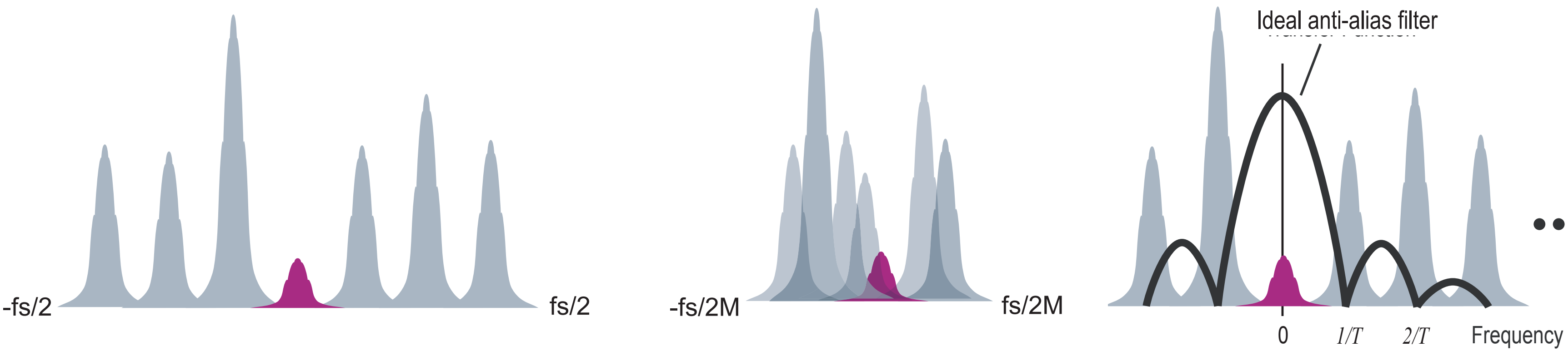
What's inside the Digital Receiver?

Davies, 2000



Everything is software controlled - clock rate, no. of taps

Sample rate conversion causes aliasing ...



How to make the RF/analog flexible?

- Push as much to digital as possible
  - With ADCs that dissipate milliwatts!
- Model the RF/analog signal processing on digital receiver

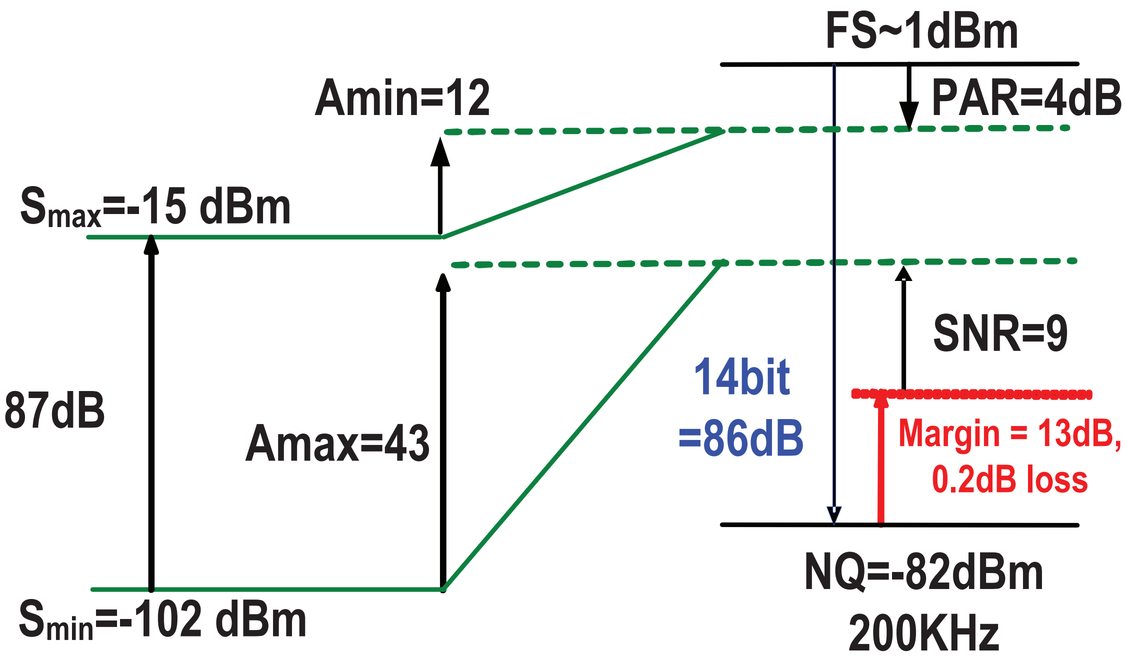
- Let's design an A/D centric RX, and work upstream towards the antenna
- Budget 10mW for A/D–today this gets us:

  8b, 40 MHz Nyquist ADC, or
  14b, 10 MHz Delta-Sigma ADC with 200 kHz bandwidth

- Choose best ADC for channel bandwidth and blocker profile
- Develop RX for GSM (200 kHz) and 802.11g (20 MHz)

Digital AGC to the max

- Variable gain amplifiers are hard to design in scaled CMOS
- What is bare minimum analog variable gain, say for GSM?



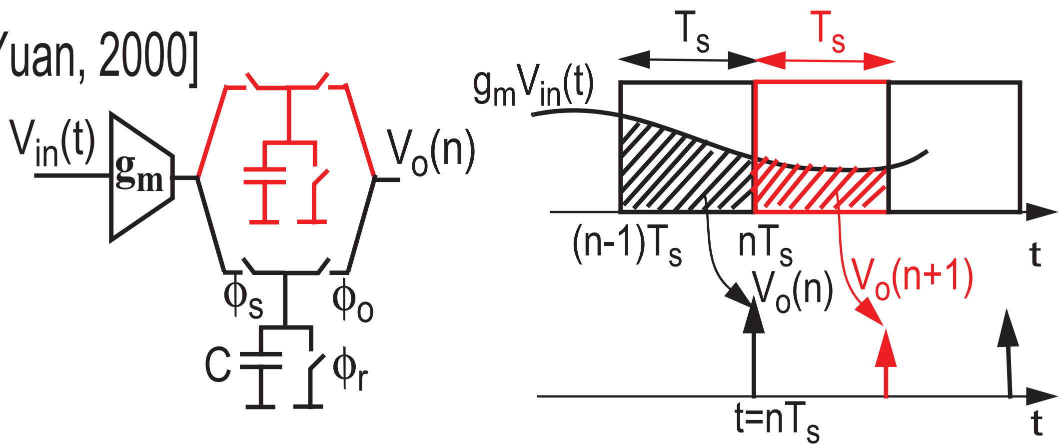
- 31 dB analog variable gain encompasses 87 dB input dynamic range
- DSP assumes rest of the burden
- Good use of surplus A/D dynamic range

Where to sample the wideband input?

- As soon as the signal of interest is at zero IF …
- Clock-driven discrete-time analog signal processing gives greatest flexibility
- With 5 GHz-wide input band, what should be the sampling frequency?
  - Only the channel at zero IF is of interest
  - Everything else is unwanted
  - But we’ll need an anti-alias filter with 100:1 range in cutoff if we sample 200 kHz to 20 MHz wide channels—impractical

Lowpass Sampler w/ Internal Anti-Alias

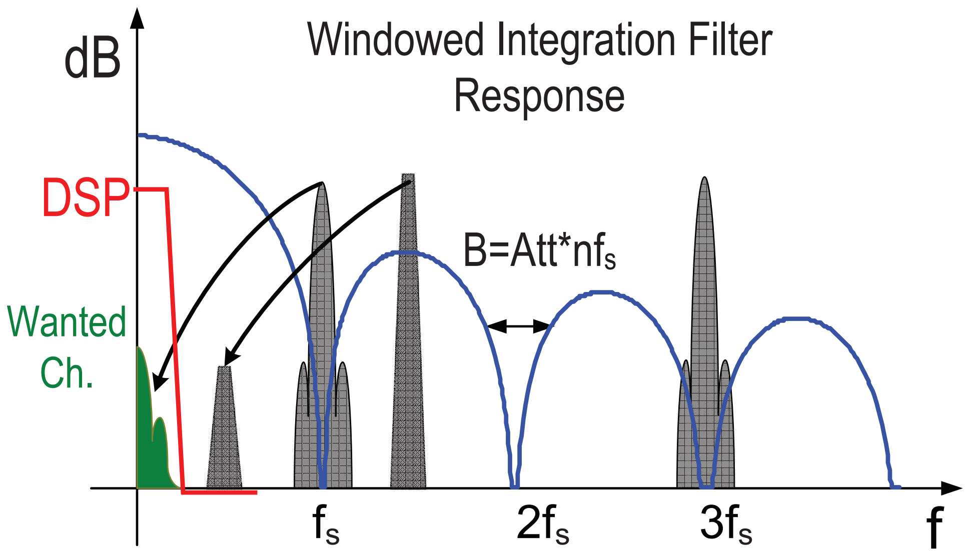
[Yuan, 2000]



$$|H(f)| = \frac{g_m T_s}{C} \left| \frac{\sin(\pi T_s f)}{\pi T_s f} \right|$$

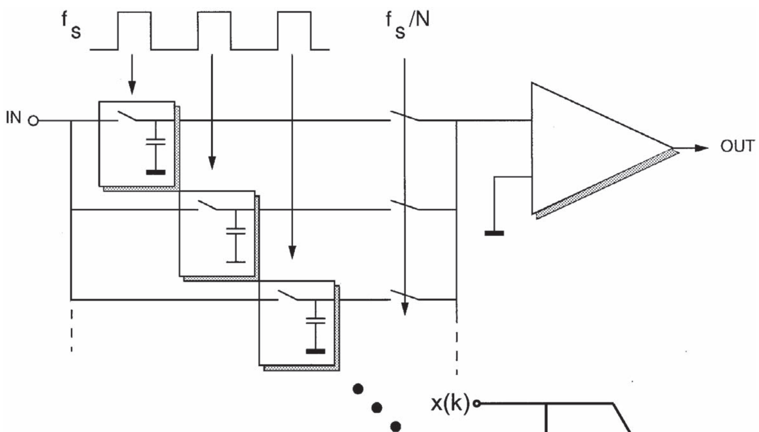
Rectangular Window Integration

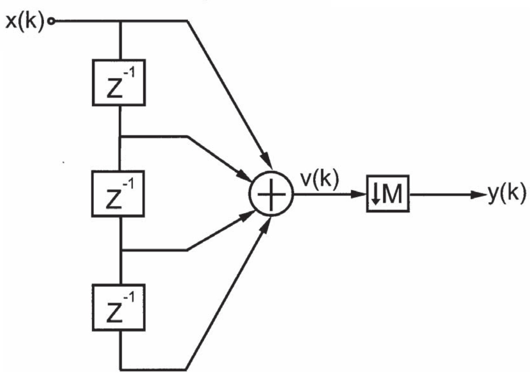
- Main-lobe passes wanted signal at DC
- Side-lobes roll off with 20 dB/ decade
- Notches @ nf_s for anti-aliasing
- Wider stop-band with higher f_s

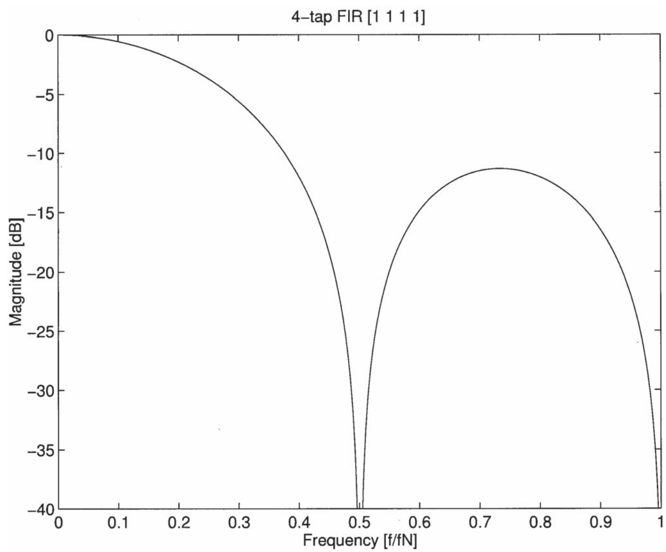


Bring Down the Sample Rate (in Analog)

- Initial sample rate may be very high, to protect the wanted channel
- A/D conversion at this rate wastes power, as wanted signal band is much lower
- Analog decimation filter? Yes ...

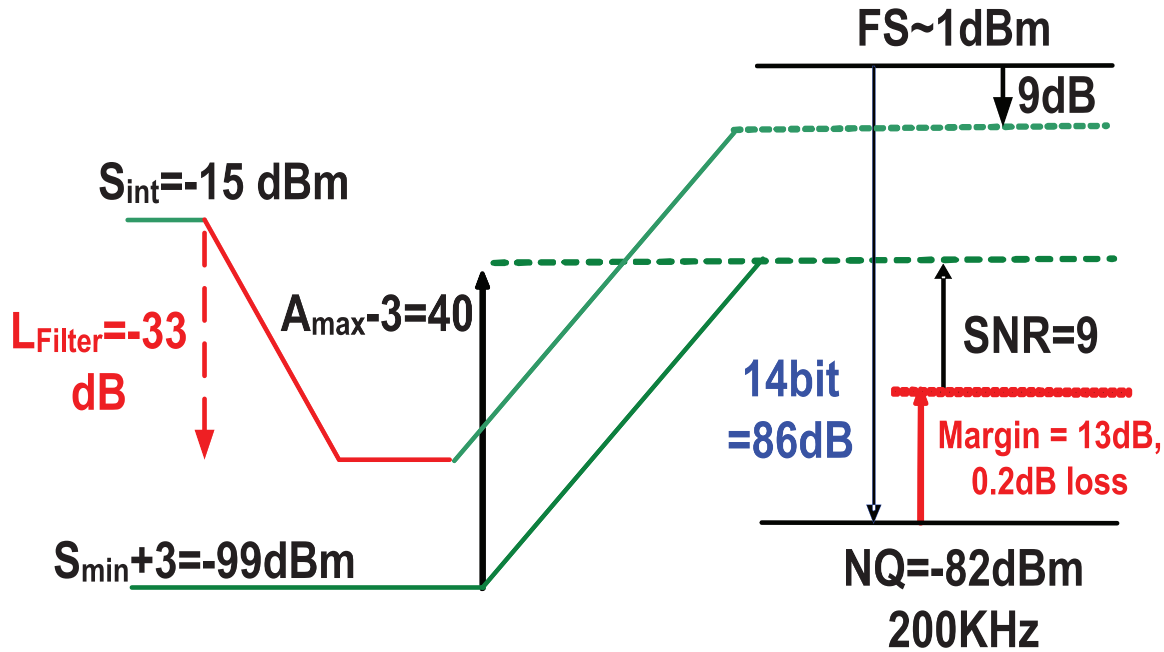






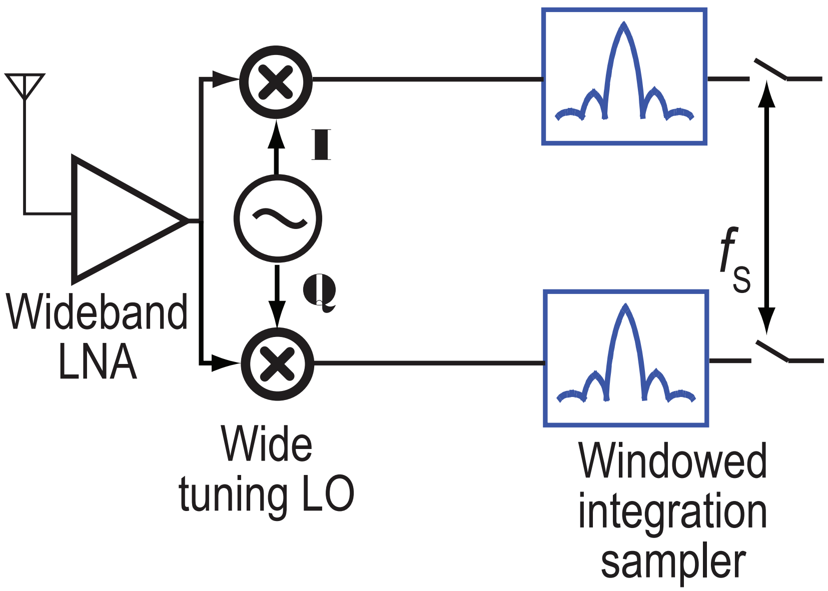
Lindfors, et al., 2003
Helsinki University

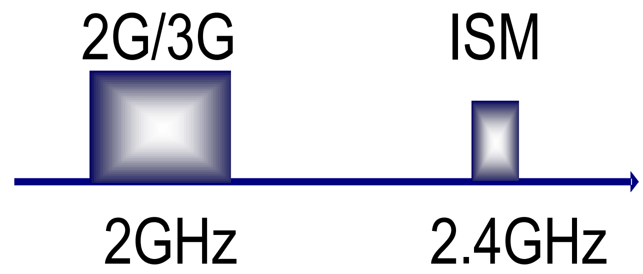
Just Enough Analog Filtering



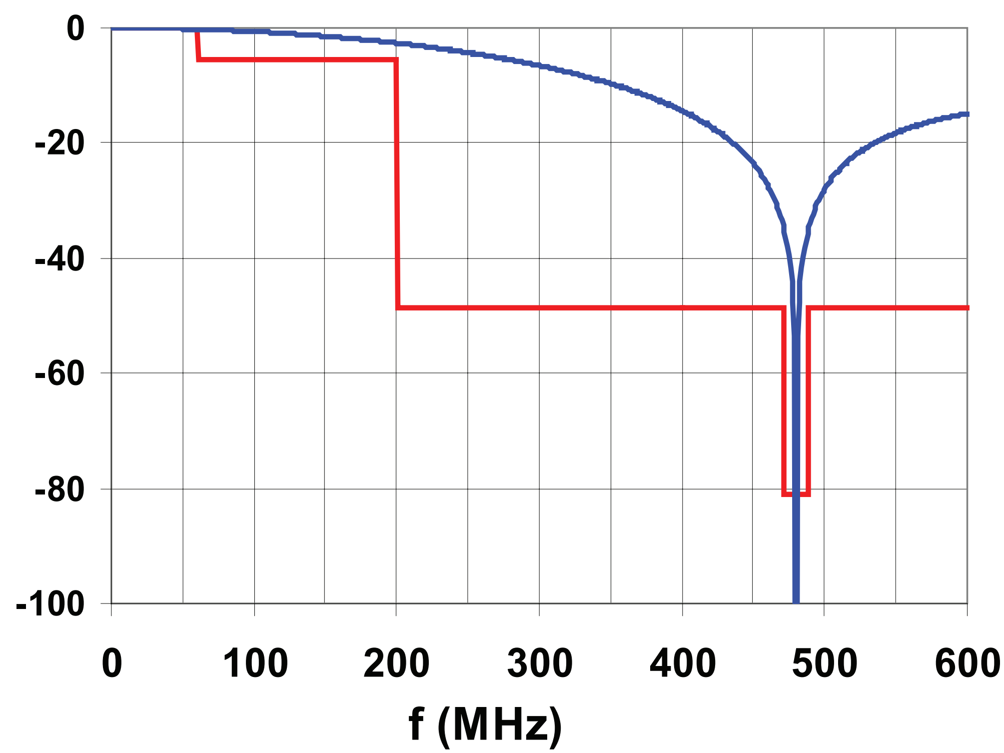
- Filter must be developed based on profile of in-band and out-of-band blockers
- Remember, there is no RF prefilter in our SDR

Evolution of RX Filter (802.11g) – 1

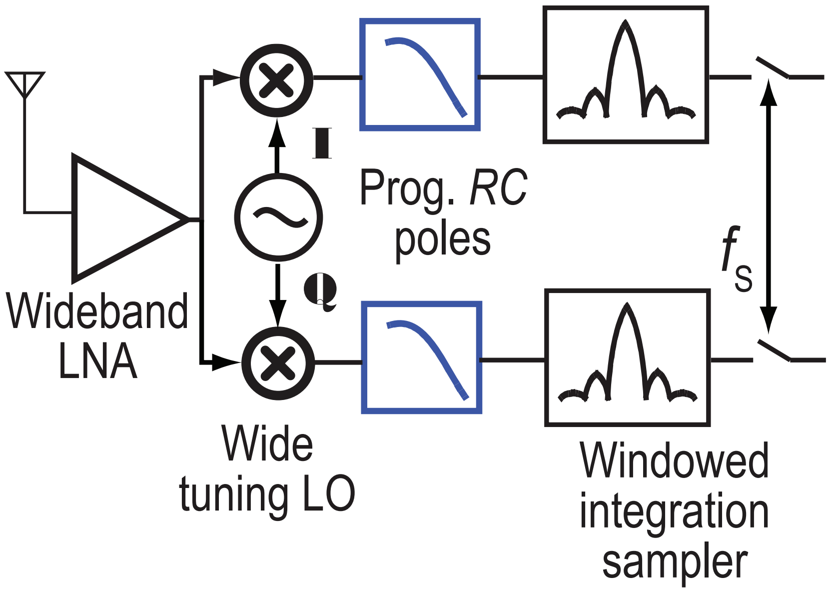


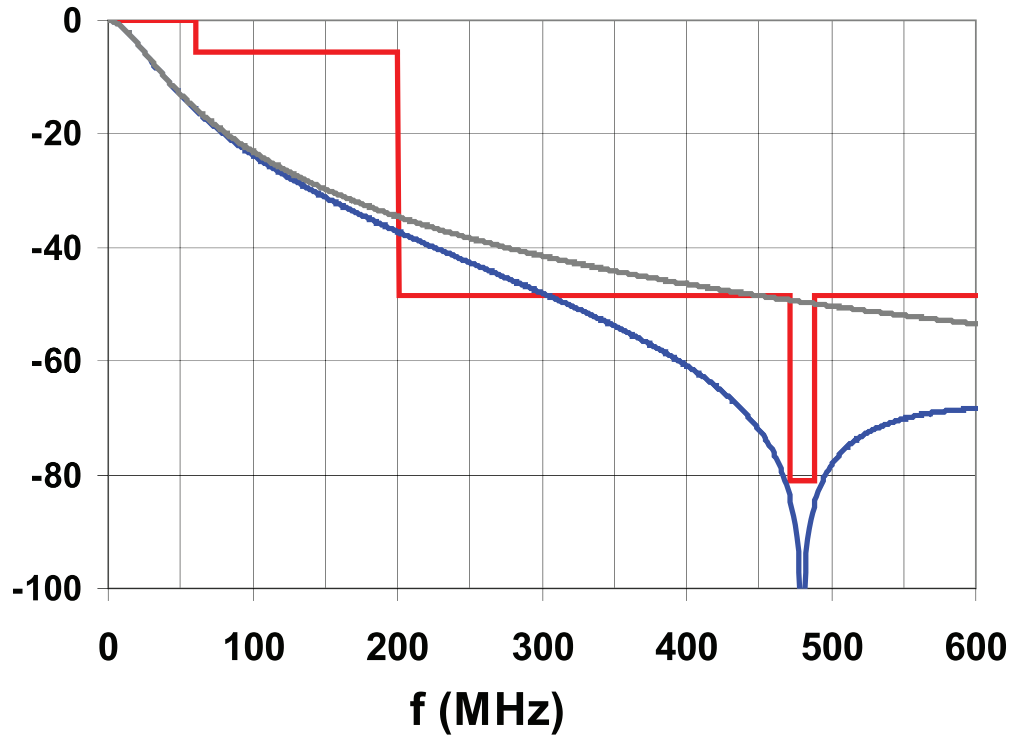


- Channel of interest lies in 2.4 GHz band, 20 MHz wide
- Choose initial sample rate of 480 MHz in windowed integrator (Why? We'll see in the next slide)
- Now first aliasing blocker is a strong CDMA cellular channel
- *sinc*() alone cannot attenuate it sufficiently (–80 dB) across 20 MHz



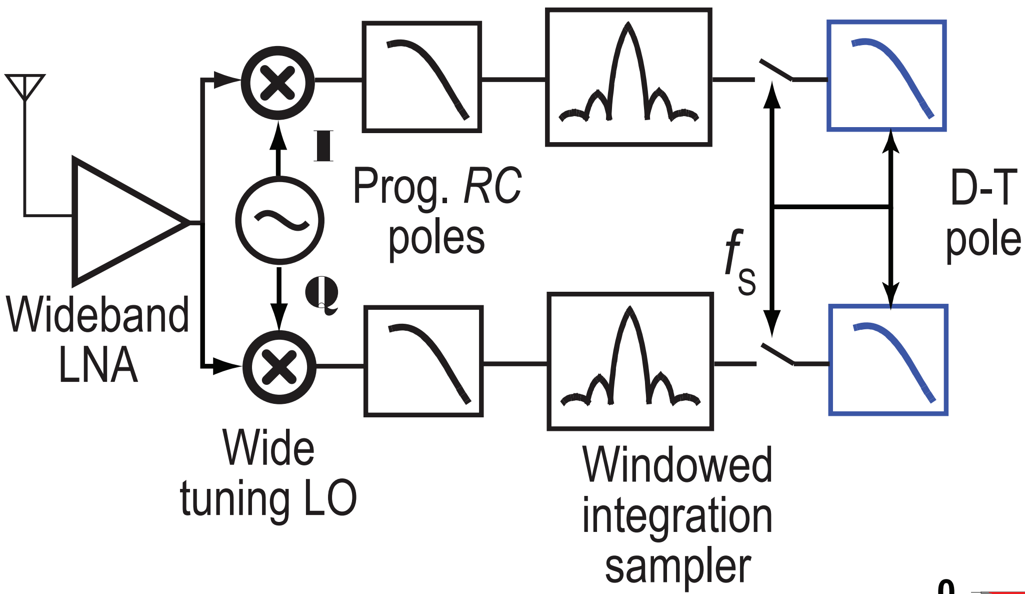
Evolution of RX Filter (802.11g) – 2

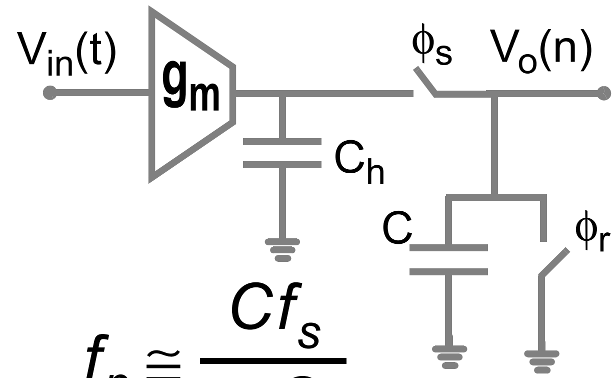




- Two passive RC poles at the mixer load gives monotonic attenuation across frequency (justifies f_s=480 MHz)
- Pole frequencies are programmable
- Small droop in channel bandwidth around DC
- Filter violates specifications between 200-300 MHz

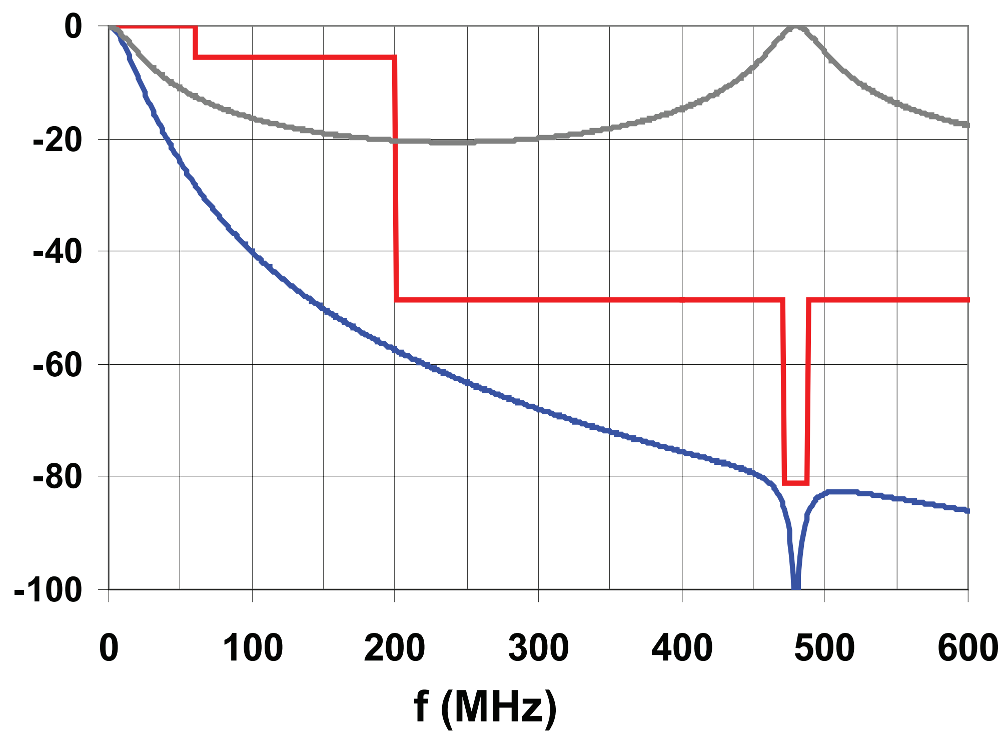
Evolution of RX Filter (802.11g) – 3



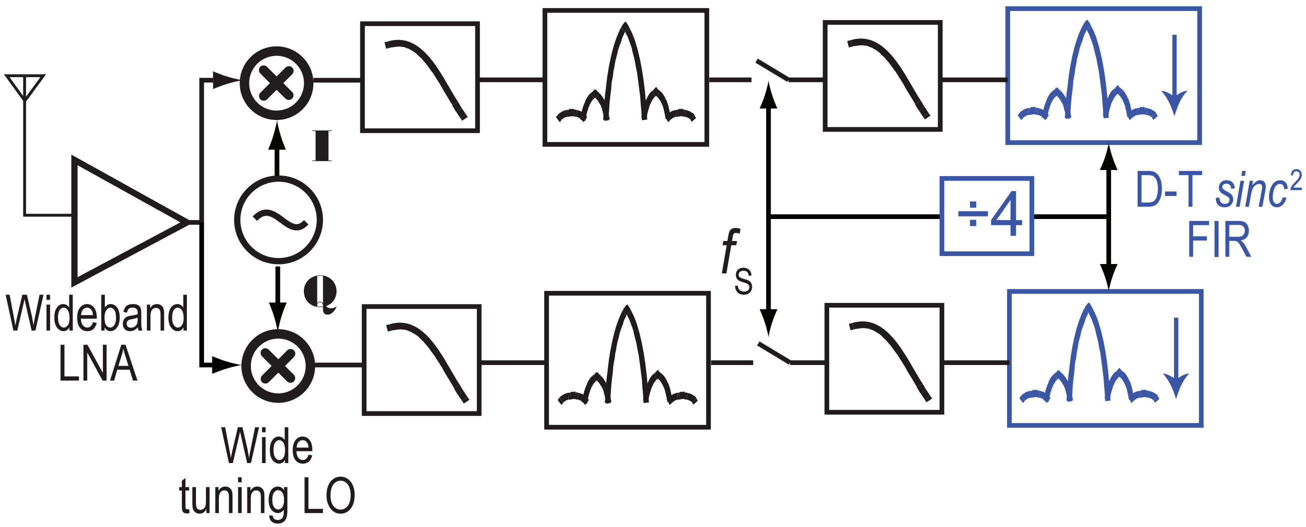


$$f_p \cong \frac{Cf_s}{2\pi C_h}$$

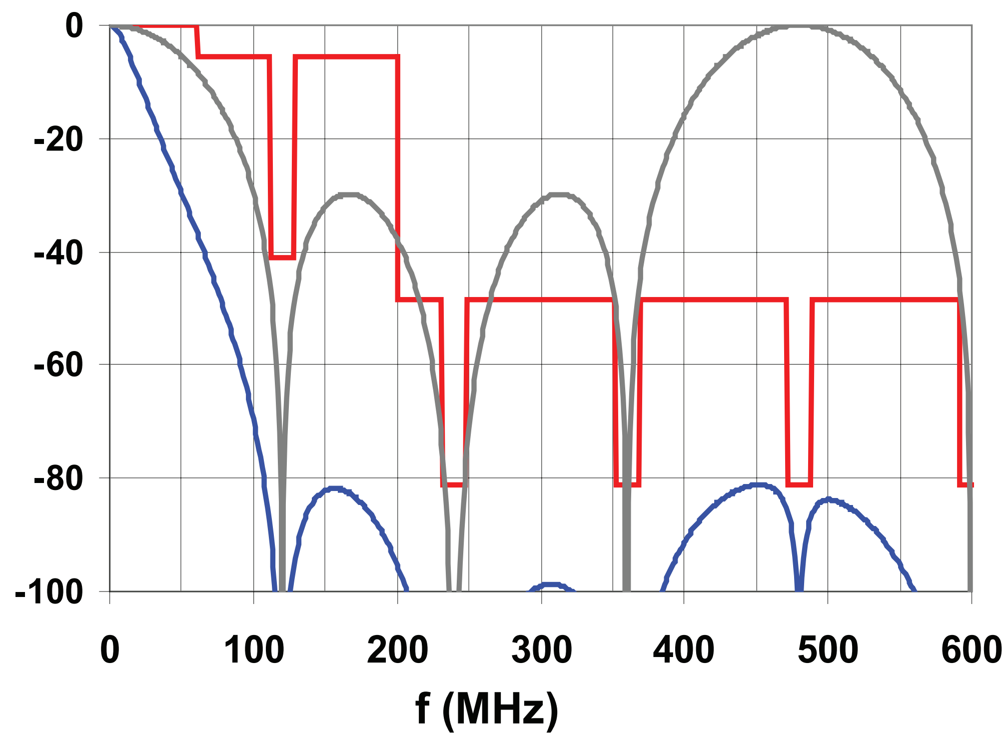
- Filter meets specs (at f_s=480 MHz), but...
- Sample rate still too high for ADC, considering channel is only 20 MHz wide
- Must decimate with suitable filter to avoid aliasing ...



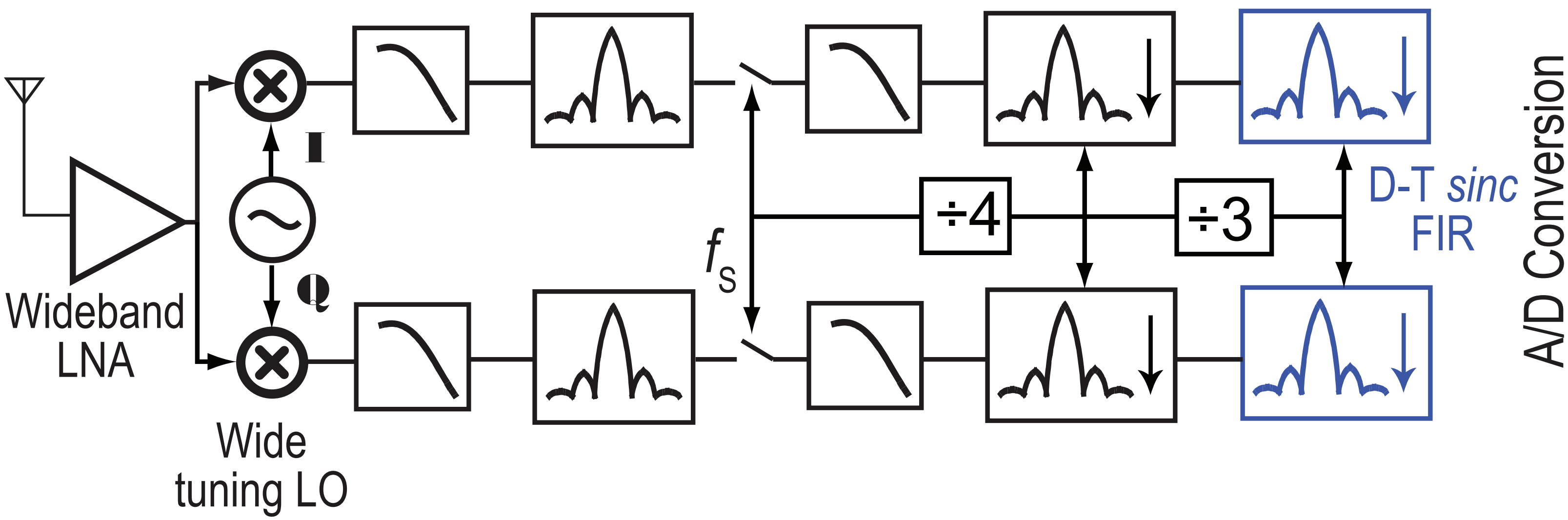
Evolution of RX Filter (802.11g) – 4



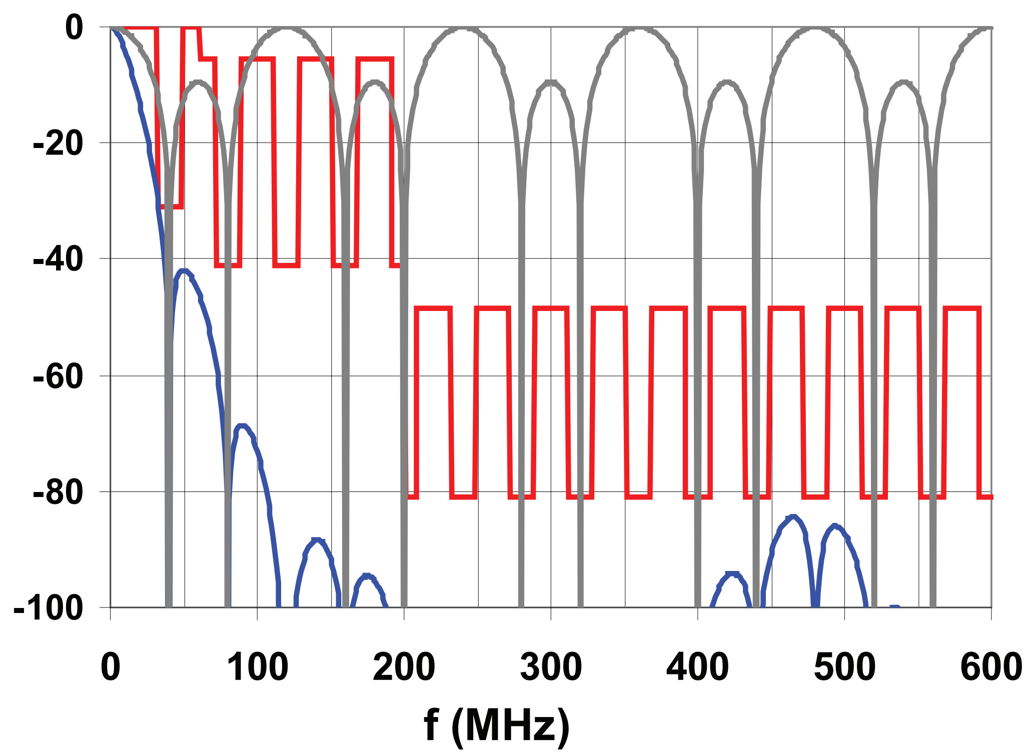
- Decimate by 4
- Now, however, new filter spec applies with 4× more anti-alias notches
- Specification met by *sinc*²() decimation FIR filter
- Should decimate further to lower power in ADC — output sample rate 120 MHz still too high for bandwidth of interest from 0 ~10 MHz



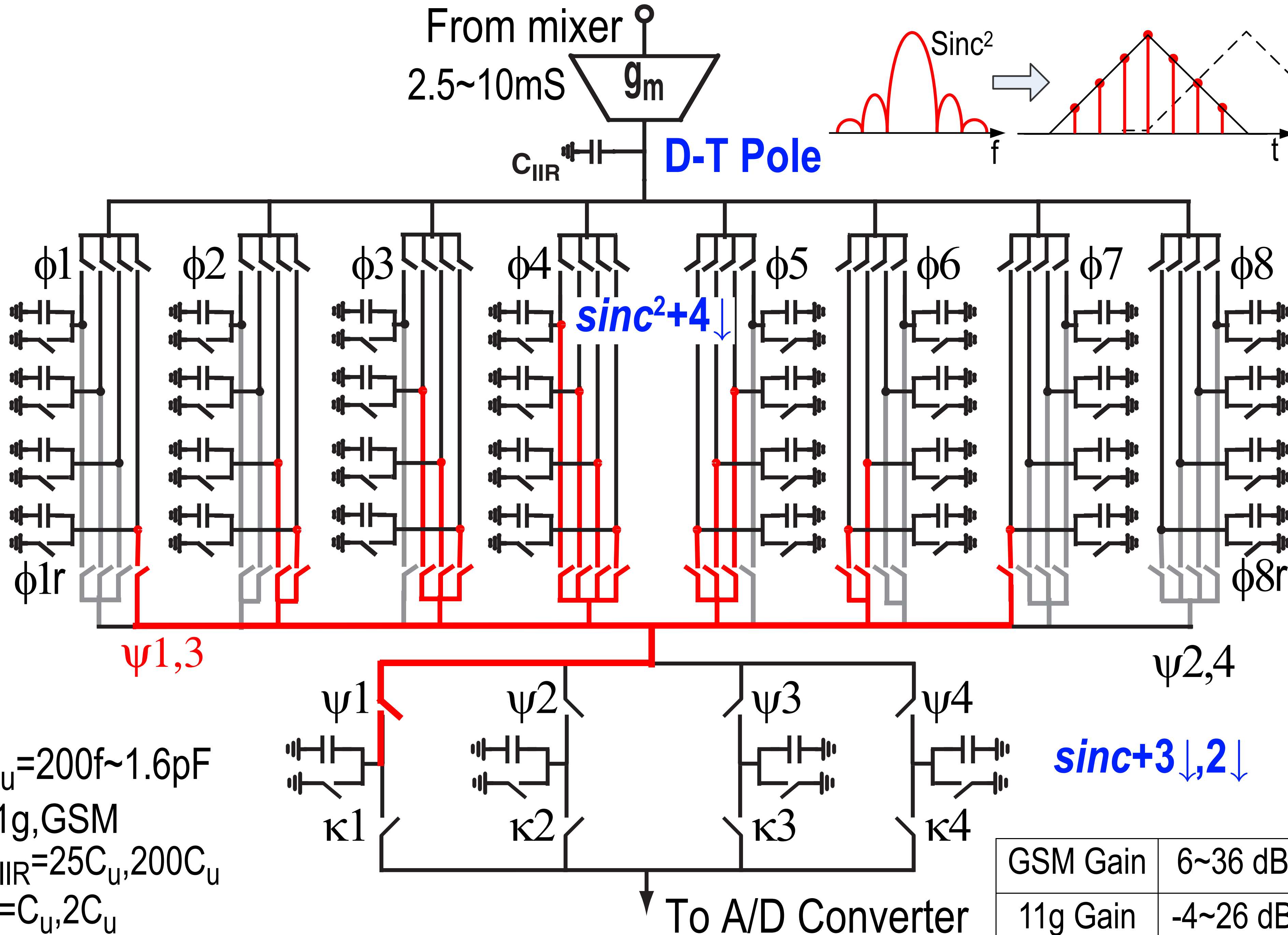
Evolution of RX Filter (802.11g) – 5



- Decimate by 3
- New filter spec has 3× more anti-alias notches
- Specification met by *sinc*() decimation FIR filter
- Now output sample rate of 40 MHz and resolution of 8b realizable by ADCs dissipating ~10 mW



Filter Realization



C_u=200f~1.6pF

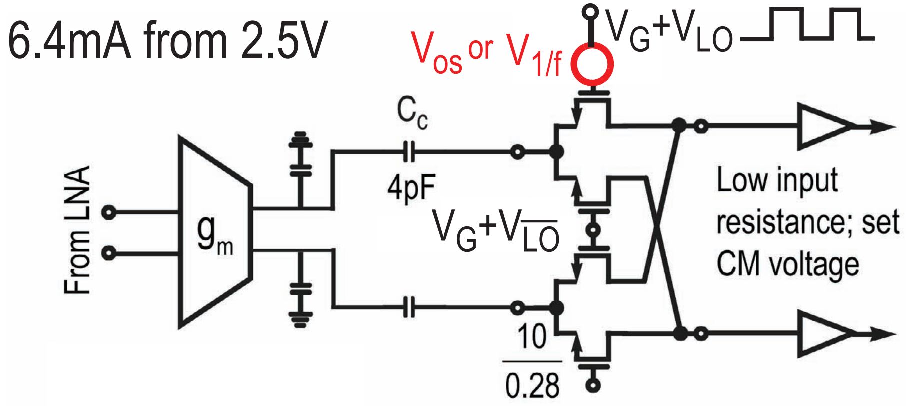
11g,GSM

C_{IIR}=25C_u,200C_u

C=C_u,2C_u

GSM Gain	6~36 dB
11g Gain	-4~26 dB

The ultimate CMOS mixer

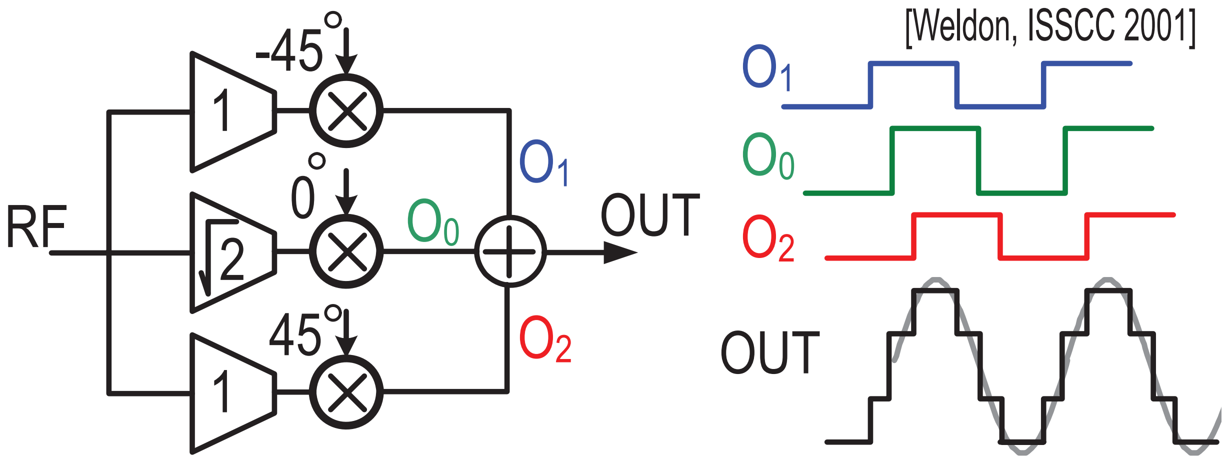


- **Passive FETs commutate signal current only**
- **Current source drive, low impedance buffer => no voltage swing on FETs**
- Main contributors to 2nd order nonlinearity:
    - Low frequency distortion of transconductor: Suppressed by C_c
    - Switch offset: Triode operation & low input impedance buffer
    - RF-LO feedthrough
- IIP2=+77dBm (@-20dBm)
- DSB NF~13dB due to g_m, flicker noise corner<10KHz (large gate area buffer)

Harmonic mixing

Unique to wideband RX

- **Hard switching mixer gives high conversion gain—good**
- **Harmonics in square-wave commutation downconvert in-band channels, e.g. 900 MHz also downconverts 2.7 GHz and 4.5 GHz—BAD!**



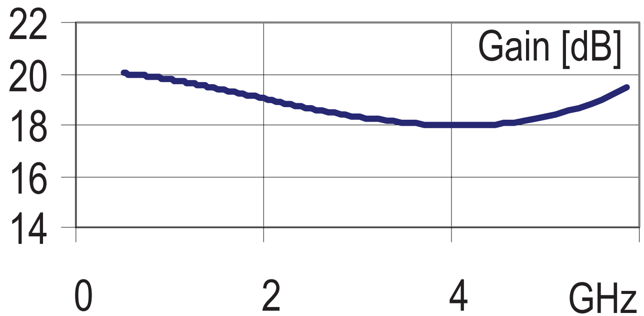
- 3-path mixer better approximates sine
- 3rd, 5th harmonic rejection is limited by phase error and gain mismatch

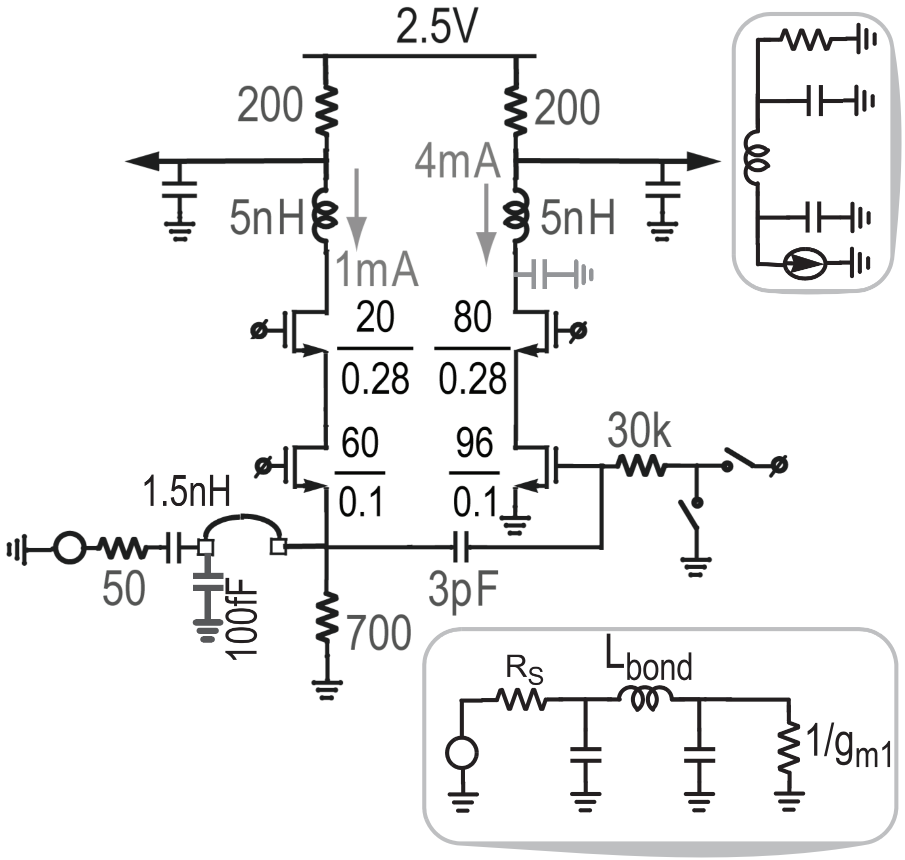
Measured	dB
3rd Harmonic Rejection	38
5th Harmonic Rejection	40

Ultimate challenge: Wideband LNA

- **Departs from conventional narrowband RF practices**

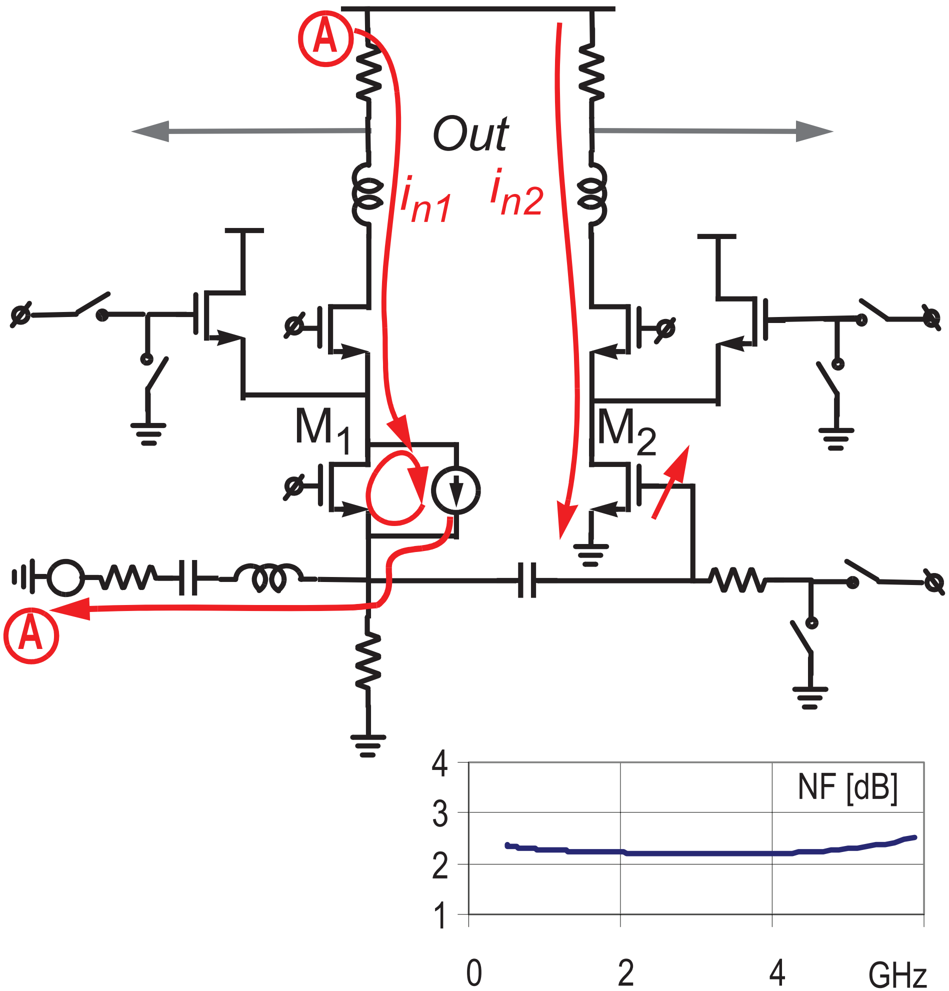
- CG provides input match
- CS to provide extra gain & single to differential
- Input matching forms a 3rd order maximally-flat ladder filter, embedding bondwire
- 3rd order maximally-flat LC ladder filter as wideband load
- Measured: 18-20dB gain and S11<-10dB over 800M-5GHz





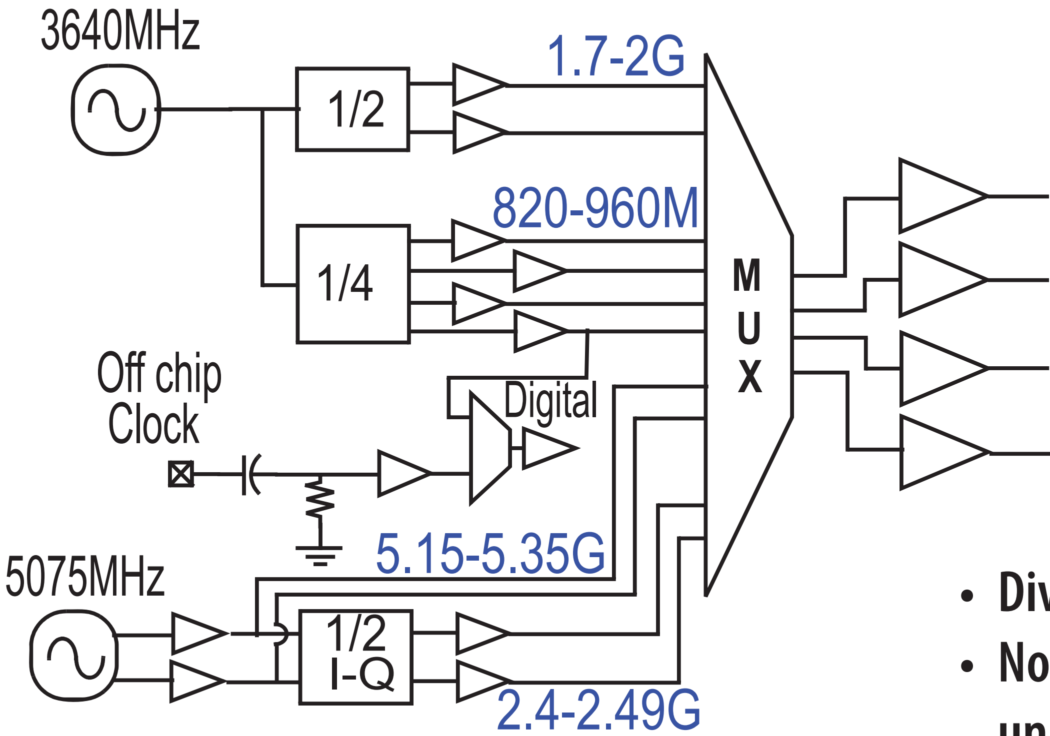
Noise cancellation

Feedforward pre-dates feedback



- CG noise is cancelled at diff. output [Bruccoleri, JSSC 2004]
- Noise cancellation has little sensitivity to all parameters and measured NF<3dB [Chehrazi, CICC 2005].
- ~20dB Gain programmability by disabling CS and dumping CG signal current

Wideband Frequency Tuning



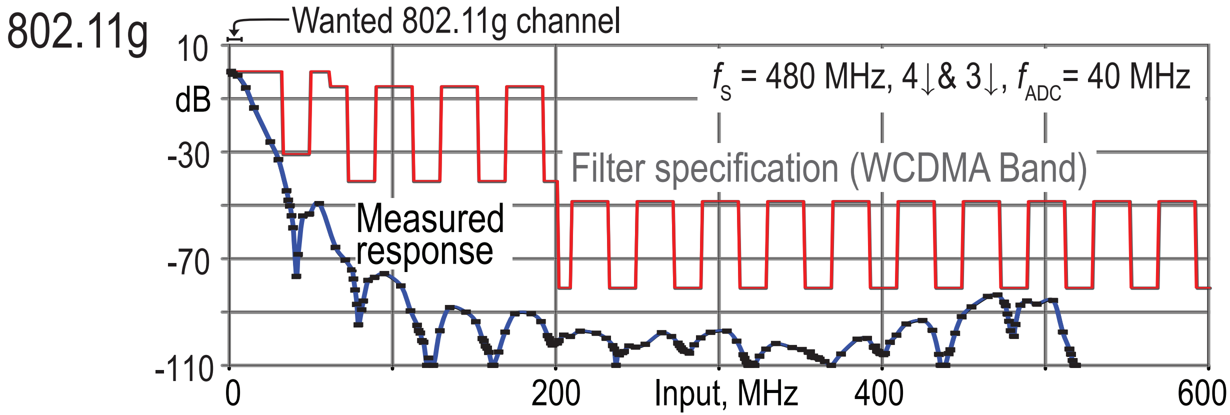
- **Divide & mux only**
- **No SSB mixers—unacceptable spurious tones**

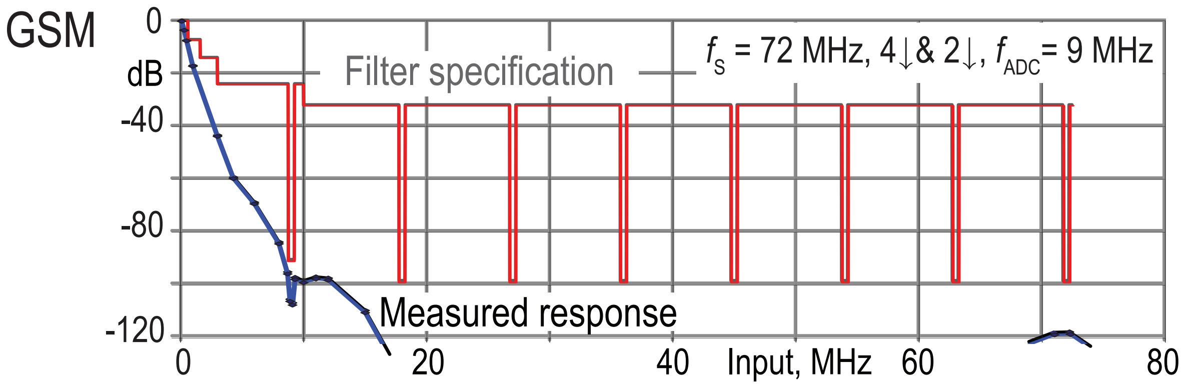
- Covers all major bands
- 2 VCO, only one is active at a time
- 21-33 mA dissipation for different bands

- **3 VCOs can give continuous frequency coverage**

On-chip Selectivity

Displaces RF preselect filter





Spurious Response

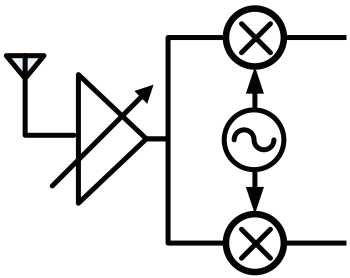
11g@ 22 MHz	-60dBr
GSM@ 4.7 MHz	-74dBr

Currents from 1V

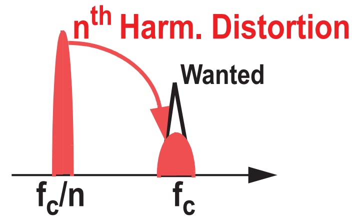
11g I_{dc}	13~28 mA
GSM I_{dc}	8~23 mA

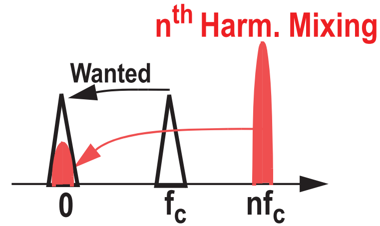
But leaves LNA/Mxr vulnerable

Exposed to intermod from every band

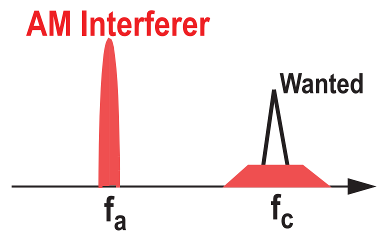


- n^{th} harmonic distortion
  - DCS 1800, 60 dBm IIP2, GSM 900M blocker
- n^{th} harmonic mixing
  - GSM 900, 110dB H2RR, GSM 1900 interferer

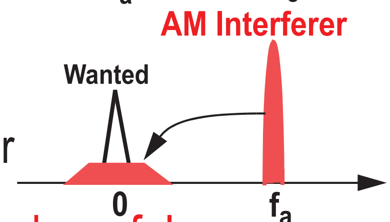




- Harmonic distortion and mixing are rare cases and waived by exceptions allowed in standards

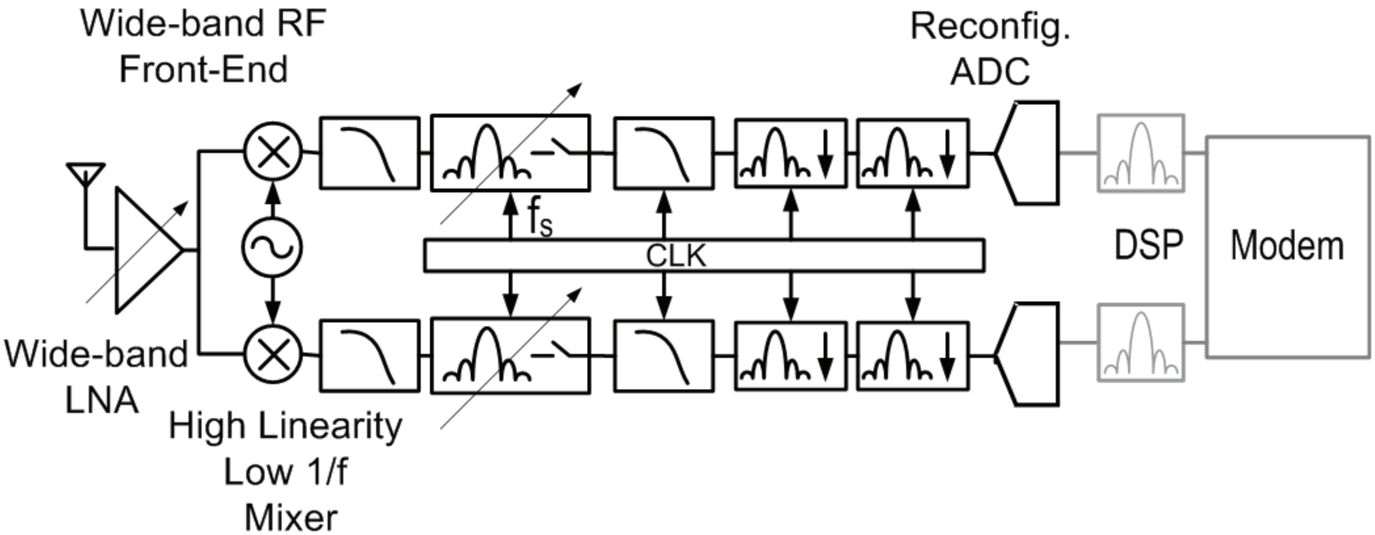


- Cross-modulation (AM blocker)
  - GSM RX: -4dBm IIP3⇨-12dBm WCDMA blocker
- AM detection (AM blocker)
  - GSM RX: 70 dBm IIP2⇨-15dBm WCDMA blocker



- Serious problem: AM blocker at any frequency can be harmful

Final Clock-Programmable SDR Receiver

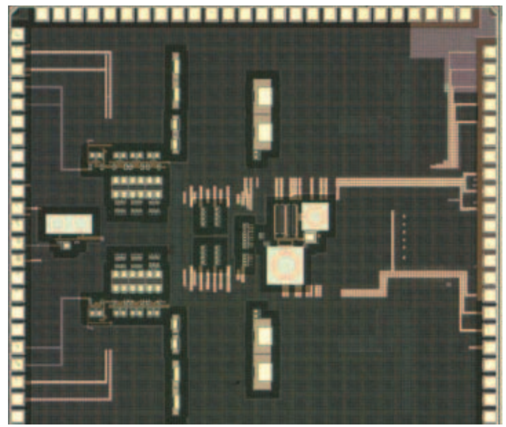


- RX tolerates AM blockers as high as -20dBm with no preselect filter
- Still higher linearity is needed from LNA and mixer

Full RX Chain Summary

	GSM	802.11g
NF (High Gain) [dB]	5	5.5
IIP3 (Mid Gain) [dBm]	-3.5	
IIP2 (Mid Gain) [dBm]	+65	+67
Power [mW]	18-52	23-57

Active Area ~ 3.8mm^2



Future Research

- Linearity, linearity, linearity!
- Concurrent reception of two or three unrelated bands, sharing hardware
- Full duplex operation such as in CDMA (without RF filters?)
- Full system demonstration with digital front-end and baseband—commercial feasibility