Part 3:

VLSI Circuits for Wireless Systems

Tutorial Outline

1 **Introduction to Wireless Communication Systems**
  - System & Medium Characteristics
  - Technological Evolution in the design of WCS

2 **Wireless Systems Design**
  - Part A: Basics of digital communications
  - Part B: Standards and example designs

3 **VLSI Circuits for Wireless Systems**
  - circuits for wireless systems-on-a-chip
  - architectural approaches to on-chip wireless systems

4 **Design Technology for Wireless Systems**
  - Design entry, validation and analysis tools

5 **Pre-designed Core Blocks and IP Issues for Wireless**

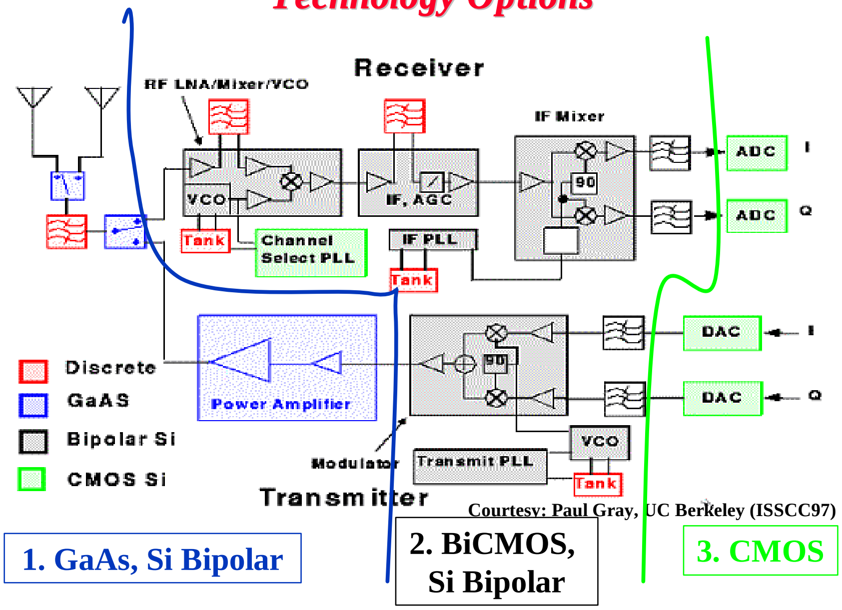
- **Future Outlook and Conclusions.**

Outline

- Introduction to RF transceiver implementation
  - Trends in portable radio systems
- Integrated Circuits in Wireless Systems
  - RF transceivers
- Building on-chip RF circuits
  - design goals
  - critical technologies
- Receiver architectures for on-chip RF processing
  - direct conversion schemes
  - base-band processing in direct conversion receivers
- Looking really far out: RF processing in software?!
- Example designs and Summary

Simplified View of a Digital Radio Link

RF Transceiver Block Diagram
Technology Options



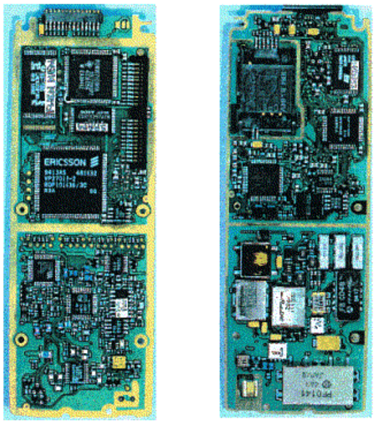
Courtesy: Paul Gray, UC Berkeley (ISSCC97)

1. GaAs, Si Bipolar

2. BiCMOS, Si Bipolar

3. CMOS

Typical RF Transceiver Implementation

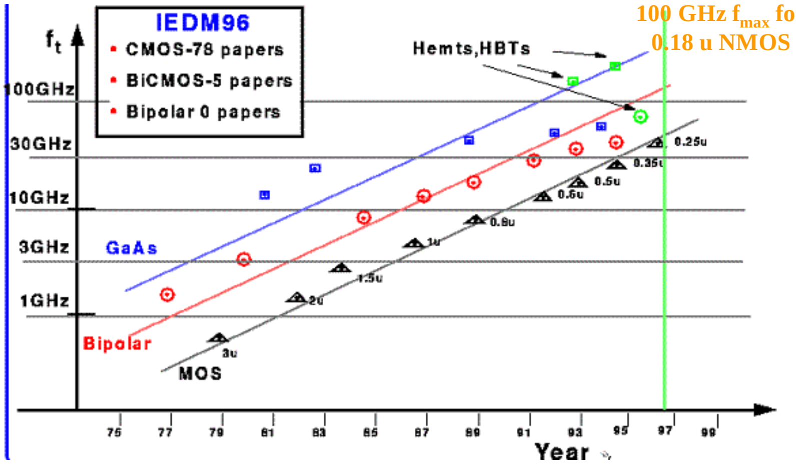


Courtesy: Paul Gray, UC Berkeley (ISSCC97)

On-Chip Wireless Systems

- Made possible by advances in
  - A. Technology scaling and improved circuit techniques
    - » Low-power CMOS/BiCMOS RF Circuit design:
      - VCOs, PLLs, Modulators, Mixers, Amps.
    - » Low-power ADC, and baseband digital signal processing
    - » Accurate modeling of parasitic on-chip parasitic RF paths
  - B. Architectural innovations in transceiver design.
- Circuit Categories:
  - – Broadcast radio receivers (FM @100 MHz RF, Walkman)
  - – Paging receivers (150-900 MHz RF, Moto Bravo)
  - – GPS receivers (2 GHz RF, Sony Pyxis)
  - – Cellular Telephone Handsets (900 MHz RF, Moto MicroTac)
  - – Wireless LAN (900 MHz or 2 GHz RF, Proxim, Plessey)

Technology Suitability for RF Design



60 GHz f_T and 90-100 GHz f_{max} for 0.18 u NMOS

Courtesy: Paul Gray, UC Berkeley (ISSCC97)

Trends in Radio Transceiver Design

- **Component Integration**
  - Higher reliability, low cost
  - RF/IF integration (Bipolar and BiCMOS)
  - IF/BB integration (CMOS)
    - DSPs and analog front ends
- **DSP Techniques for Radio**
  - Rapid and flexible prototyping
  - Greater accuracy and adaptability
  - Traditionally DSP used for premodulation and post detection such as codecs but now ADC is moving closer to antenna enhancing the role of DSP algorithms.

On-Chip RF Circuit Components

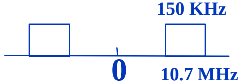
- **Resonators**
  - interconnect spirals
    - 1-10 nH, with Q=4-8 at 2 GHz, f_{self} approx. 3-10 GHz
  - bond out wires
    - 1-5 nH, with Q=20-40 at 2 GHz
  - etched cavities for improved self-resonance (Abidi, UCLA)
  - micro-machined structures (MEMS) for variable capacitors (Boser, UCB)
  - on-chip acoustic resonators etc.
- **On-chip low-noise amplifier example (UC Berkeley)**
  - inductor tuned common-source amplifier using on-chip spiral and bond-wire inductors
  - Noise Figure < 5 dB, Voltage gain = 22 dB, Power @3.3 V = 41mW
  - On-chip CMOS amps built from 770 MHz to 1.9 GHz, NF 3-6 dB.

IC Design for Radio Receivers

- Conventional radios were built using discrete VHF/UHF bipolar transistors, FETs and discrete passive components.
- Since 1970s technological progress made use of Si ICs
- Circa 1977:
  - On-chip IF amp + FM demodulator + Power amp
  - Off-chip inductors, capacitors, ceramic resonators
- IC particularly suitable for high gain direct-coupled differential limiting amps
- Main problems
  - thermal feedback, coupling through power-supply, parasitic inter-pin coupling

Integration of FM Receivers on Chip

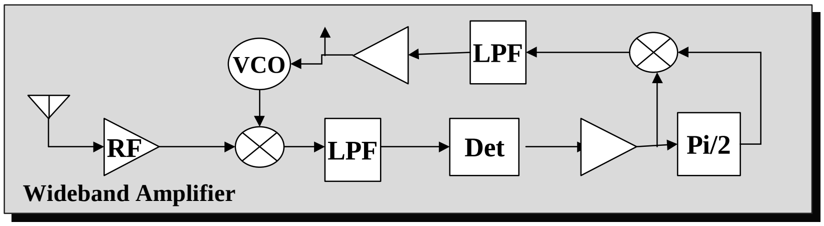
- Reduce amount of RF filtering
- Reduce number of tuned components
- Bring RF amp on-chip (use off-chip tuned load if necessary)
- Filters for greater selectivity and image rejection should be on chip
- Conventional FM Receiver: 100 MHz RF, 10.7 MHz IF
  - Image channel outside 20 MHz band.
- Choice of high IF suppresses image frequency
  - but it is difficult to make on-chip active filters with high dynamic range and low power.
  - need 10.7 MHz BP with 150 KHz passband.



- Very diverse carrier frequency and bandwidth requirements across applications.

Low IF FM Receiver

- Lower IF so that on-chip LP filters may define channel BW
- Zero IF has no image but can not use limiting amp to remove AM noise
- Single-chip FM Radio
  - FM swing limited to +15KHz, First LPF with 100 KHz cutoff
  - 15 cap, 2 inductors, 8mA drain from 4.5 v



DBS TV Receivers

- Transmission at 12 GHz
- Conversion to first IF (900 MHz to 2 GHz) in receiver antenna
- ICs have been developed for first IF onwards -- miniature DBS receivers in TV sets and VCRs
- 12 GHz down-converted to 0.95 - 2.1 GHz
  - passed through BPF and then down-converted to 400 MHz BPF
  - passed through PLL FM discriminator
  - => BB TV signal

Paging RX

- Modern Pagers use digital signaling at 500 bps
- Small size and power
- Bellboy: 4V supply, 10 transistors in entire receiver
  - Single conversion super-heterodyne with 6 KHz IF
  - capacitively coupled 10 KHz LP filter for channel selection

Building On-Chip RF Circuits

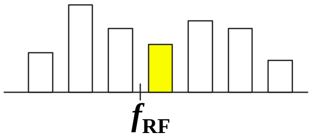
- Design goals:
  - minimize power dissipation
  - minimize cost, size,
  - adaptable to multiple RF transmission standards, easy upgrade, maintenance (through software)
- Design issues:
  - available channel bandwidth, required spacing, data rate
  - receiver sensitivity and noise figure
  - image rejection, robustness against close-in strong interferers
  - transmit power
  - power consumption in RX, TX, standby
  - silicon area.

Trends in On-Chip Wireless System Design

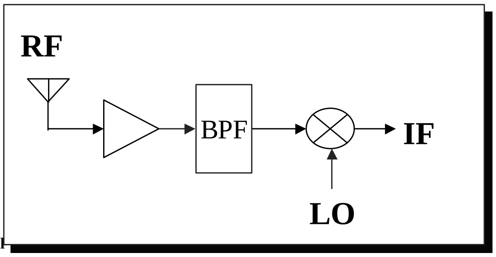
- Key ingredients
  - maximize digital components, minimize analog, passive elements
  - move digital processing to as early in the receiver path as possible
  - simplify design requirements of essential analog components
  - use low-power (digital) circuit/architecture design techniques
  - sophisticated base-band DSP particularly to support multiuser systems
- Analog portions continue to dominate power consumption
  - only marginal increase in power consumption due to increased base-band digital signal processing
  - DS-CDMA RX in two chips using 0.8 u CMOS (32 MHz chirp) [UC Berkeley 1992]
    - analog front-end: amp, subsampling, demod, ADC 107 mW
    - digital base-band signal processing 27 mW

Architectural Evaluation for On-Chip RF

- Receiver architectures
  - superheterodyne RX (double conversion)
  - homodyne RX (direct conversion)
  - digital conversion (IF sampling)
- Transmitter architectures
  - two-stage up-conversion
  - direct up-conversion



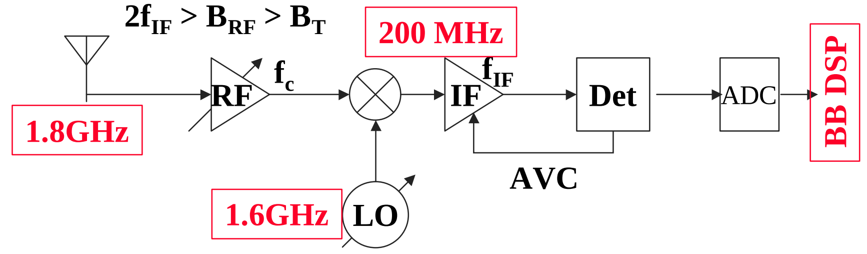
•Move RF signal to a band for inexpensive processing.
•Condition signal to minimize intersymbol interference
•Extract channel.



Super Heterodyning

- Introduced by Armstrong in 1918:
  - the input signal is first amplified at RF
  - then converted to IF using an offset-frequency LO
  - substantially amplified in a tuned IF strip using highly-selective BP filters
  - usually, $f_{IF} < f_{LO}$, therefore when picking up channel at $f_c = f_{LO} - f_{IF}$ we also pick up channel $f_c' = f_{LO} + f_{IF}$ which is called the image frequency.

$2f_{IF} > B_{RF} > B_T$



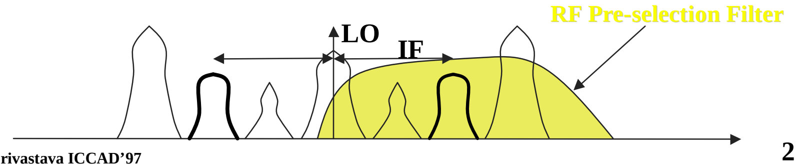
$f_{LO} = f_c \pm f_{IF}$

Image Rejection and Channel Selectivity

- Image rejection
  - IF needs to be large so that 2*IF is large and a front-end filter can be designed to reject the image channel.
- Channel selectivity
  - IF needs to be low so that a high Q filter can be realized to “select” the desired channel.

Super-heterodyning (continued)

- RF provides image-channel rejection
- IF provides adjacent-channel selectivity
  - tune f_c to desired channel and tune f_{LO} to $f_c + f_{IF}$ so that correct frequency if obtained at the mixer output.
- f_{IF} must be sufficiently high so that the image channel in the stopband of the RF preselection filter else IF filter will pass this channel unattenuated in its own image passband.
  - For instance, 10.7 MHz IF in FM Rx guarantees that image channel lies outside of the 20 MHz wide FM band.
  - 43. MHz IF in TV Rx, 90 MHz IF in cell phones.

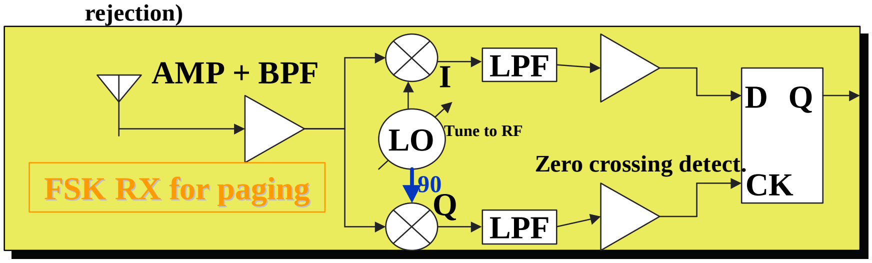


IF Issues

- High IF amplification and filtering consumes power and requires a large number of off-chip passive components.
- Wireless Rx handle weak signals that may exist next to very strong channels in the same band.
- Single-chip broadcast FM RX sometimes use image-reject down-converters where the entire RF spectrum is down-converted to an IF in two identical mixers driven by quad phases of a local oscillator (LO). The down-converted signals are then added.
  - Down-converts desired channel to IF with the same phase in the two branches, but anti-phase for image channels, thus image channel is rejected.

Direct Conversion

- Zero IF => LO will translate the desired channel to 0
- Received RF signal is amplified and filtered as baseband rather than an IF
  - lower current drain in amplifiers, active filters
  - easier image rejection
- Because the image channel will now fold-over the desired channel, therefore, quad downconversion is a must (provides upto 20-30 dB image rejection)
  - In theory, no need for RF preselection filter (but supplies 30-40 dB image rejection)



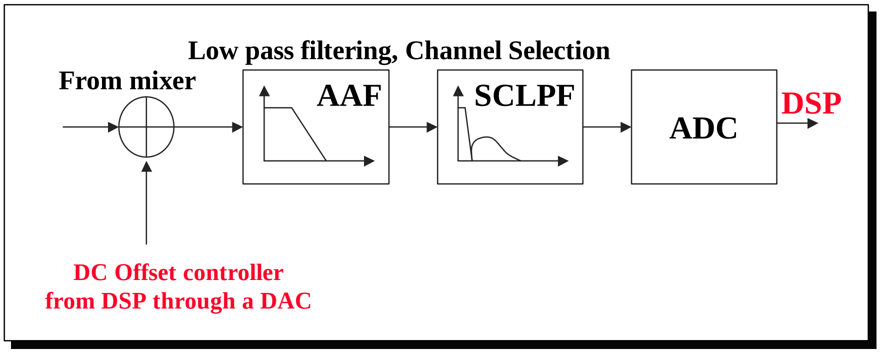
- Old idea (> 40 years) but first 1200 bps FSK RX IC built in 1992.

Issues and Solutions in Direct Conversion RX

- Low frequency errors
  - circuit related noise and offsets (5-10 mV) are much larger than the received signal (10-100 uV) which also contains useful LF component
- Approaches:
  - optimize coding for a balanced DC
  - utilize DC balanced preamble to detect start of data
  - low IF architectures
    - move IF from DC to a low frequency where digital or analog IF BPF can be used
    - worsened image rejection. Use quad downconversion and RF filtering
  - wideband double conversion
- Sensitivity to phase jitter between I and Q streams
- PLL lock-up at LO since signal frequency and LO are close together.
  - LO leak-out to antenna.

Base-band Processing in Direct Conversion RX

- **Recall in direct conversion after RF bandpass filtering the quadrature down-conversion translates the RF spectrum directly to base-band where is it amplified and passed through LPF for channel selection.**



Digital Conversion RX

Approach:

- **Translate to low IF**
- **Digitize**
- **Input to DSP**

Use sampling aliasing to realize a demodulator.

LNA -> BPF -> LO -> BPF -> SH/ADC

-> Digital I, Q demodulator -> I, Q detector

- **Let B be the bandwidth of the channel to be extracted**
  - for digital conversion, $IF + B/2$ must be a multiple of B
  - $IF + B/2 = k.B$ => sampling freq. $= 4.IF/(2k-1)$

Digital Conversion

Received IF signal, $y(t) = \mathrm{Re}\{ s(t)\, e^{jw_{IF}t} \}$
$= \mathrm{Re}\{ [(p(t) + j\, q(t)] [\cos wt + j \sin wt] \} = p(t) \cos wt - q(t) \sin wt$

let $w_{IF} + B/2 = kB$ or $w_{IF} = (2k-1)B/2$
let $T = Pi/B$

then $y(nT) = y(t) \mid t=nT$
for n even, $n = 2r$, $y(nT) = p(rT1)(-1)^r$ $T1 = 2.T$
for n odd, $n = 2r - 1$, $y(nT) = q(rT1 - T1/2)\,(-1)^{r+k+1}$

Band-pass samples contain low pass signals p, and q.

Digital Conversion

- **Advantages**
  - no phase gain imbalance
  - digitization at IF removes DC offset problem in direct conversion receivers
  - channel selectivity through digital filtering
    - more flexible, programmable
- **Disadvantages**
  - demands IF rate ADC speeds
  - IF filtering may be expensive.

Transmitter Architectures

- Direct up-conversion
  - analog of direct conversion RX
  - baseband I/Q channels directly modulated to RF
    - not possible for RF > 70 MHz
- 2-stage up-conversion
  - use low IF (70-100 MHz)
- FSK transmitters
  - feed the signal directly to a frequency modulator
  - for 800-1000 MHz and beyond.
- Direct Digital Frequency Synthesis (DDFS)
  - use DSP to produce desired signal digitally
  - pass through DAC and filter to smooth out the final signal
  - practical upto 1 MHz at 1 W.

Far Out? RF Processing in Software!

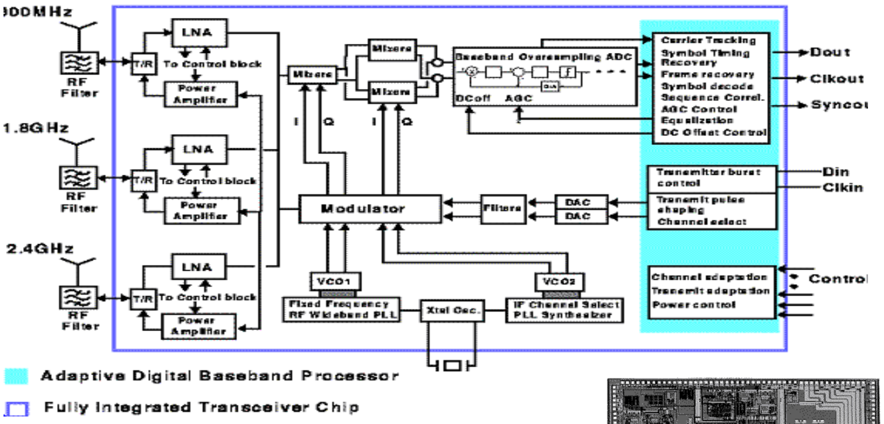
V. Bose, MIT 1997

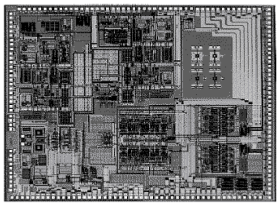
- The hardware is used only to convert the desired RF band down to IF
  - use a multi-band frontend to select center frequency and width of an RF band (from 2 MHz to 2 GHz), sample at 12-bit resolution under software control (Rockwell 95x wideband rx)
- IF is sampled and quantized and streamed to memory
  - 12-bit converter from Analog devices (max rate of 40 MSPS) or 20 MHz IF bw
  - use DMA to transfer sampled data directly to sw application
- Processing of digital wide-band IF signal in software.
- Example:
  - FH radio in the 2.45 GHz ISM band using FSK
  - 4.8 MHz wide IF band sampled at 10 MSPS @ 12 bit, FH @ 1000 / sec.
  - Transmission at 325 kbps, reception at 64 kbps
- Software controls FSK frequency selection, spacing of hopping channels
  - FSK waveforms are precomputed for each hop frequency
  - 2.2 us for IF waveform for a bit on a 180 MHz PPRO machine => 450 kbps.

Software Radio (continued)

- **Reception**
  - **RX detects a transmission, synchronizes to it**
  - **RX looks for one of the two valid waveforms for each hopping frequency and FSK demodulation**
    - » **track hopping sequence (0.5 us/hop)**
    - » **obtain FSK lock (66.3 us/bit)**
    - » **demodulate the bits once sequence is locked (4.5 us/bit)**
  - **deframe bits (5.7 us/bit)**
  - **extract IP packets (4.6 us/bit)**
  - **pass on the IP packets to host IP layer**
- **each info bit requires**
  - **storage = bit period * sampling freq. = 16 samples = 32 bytes of storage**
  - **or upto 11 kbytes of storage after framing and modulation to IF waveforms.**
- **Highly flexible processing: radio in 520 lines of C++ code.**

Example Design 1: UCB DECT CMOS Adaptive RX





0.6 um CMOS, 7.5mm x 6.4mm die size.
55dB image rejection, mostly from IR mixer.
198 mW power. RX gain max 78 dB, min 26 dB

Courtesy: Rudell, et al, ISSCC'97

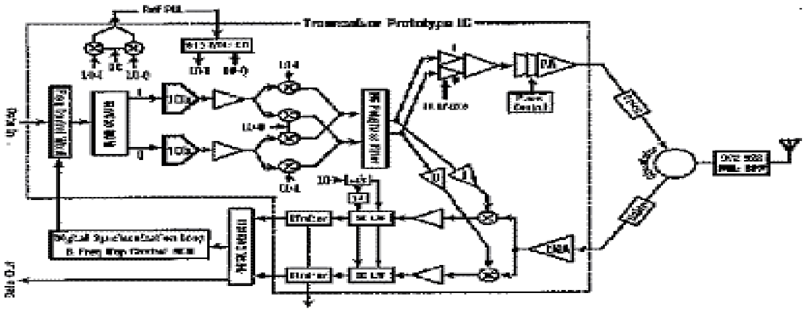
Example 2: 900 MHz CMOS WLAN RX

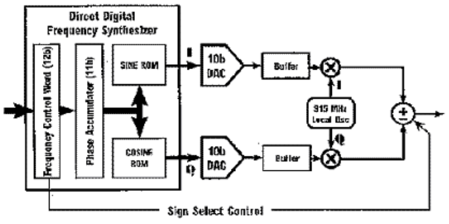
Abidi et al, UCLA ISSCC'97

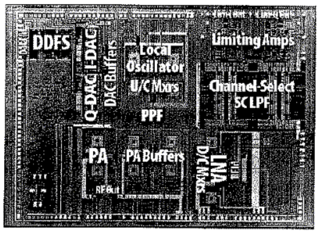
- **1 um CMOS p-epi on p+, 10.5 x 7.3 mm.**
- **Frequency-hopped 900 MHz Spread-spectrum LAN, 150 khops/sec (max), 20 khops/sec (typ)**
- **2-160 kbps data rate**
- **Direct conversion RX**
- **Fixed VCO, DDS offset frequency**
- **RF sensitivity: -105dBm@10dB SNR (NF=8.5 dB)**
- **Channel filter: 220 kHz passband, 57 MHz stopband**
- **3 volt supply, 120 mA active RX current, 100 mA active TX current**

©R. Gupta, M. Srivastava ICCAD'97

UCLA 900 MHz Transceiver Block Diagram







Summary

- RF transceivers are migrating from ..
  - super-heterodyne architectures with analog demodulation, using SAW, ceramic RF and IF filters on board-level designs
- … to
  - digital demodulation, (semi)direct conversions and digital baseband processing on a single CMOS chip.
- Integrated designs often support multiple standards
- Key problem in continued evolution towards IC solutions are
  - CAD tools for highly accurate modeling of on-chip coupling and parasitic effects, package modeling, inductor design, et cetra.
  - Process enhancements to support high-Q resonators, filters.
  - Exploitation of bands above 2.5 GHz using SiGe or hybrid Si/III-IV approaches.