

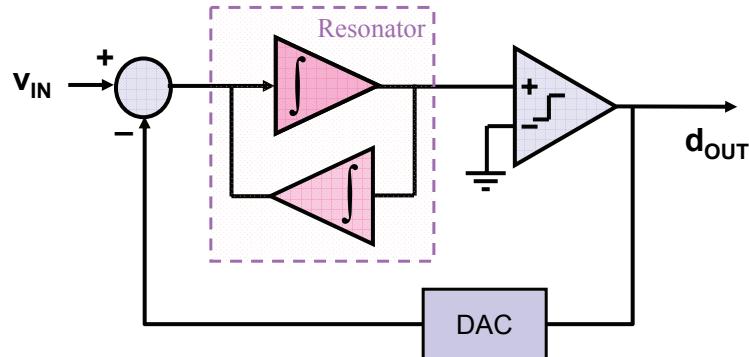
# Administrative

- Project :
  - Discussions & report submission on Frid. Dec. 4<sup>th</sup>  
(make appointment via sign-up sheet)
  - Student presentations Dec. 3<sup>rd</sup> & Dec. 8<sup>th</sup>
- Office hours @ 567 Cory :
  - Tues. Dec. 8<sup>th</sup>, 4 to 5pm
  - Wed. Dec. 9<sup>th</sup>, 10 to 11am
- Questions can also be asked via email

# EE247 Lecture 26

- Bandpass  $\Sigma\Delta$  modulators
- ADC figures of merit
- Term project student presentations
- Examples of systems utilizing analog-digital interface circuitry (not part of final exam)
- Acknowledgements

## Bandpass $\Delta\Sigma$ Modulator



- Replace the integrator in 1<sup>st</sup> order lowpass  $\Sigma\Delta$  with a resonator  
 $\rightarrow$  2<sup>nd</sup> order bandpass  $\Sigma\Delta$

## Bandpass $\Delta\Sigma$ Modulator Example: 6<sup>th</sup> Order

Measured output  
for a bandpass  $\Sigma\Delta$   
(prior to digital  
filtering)

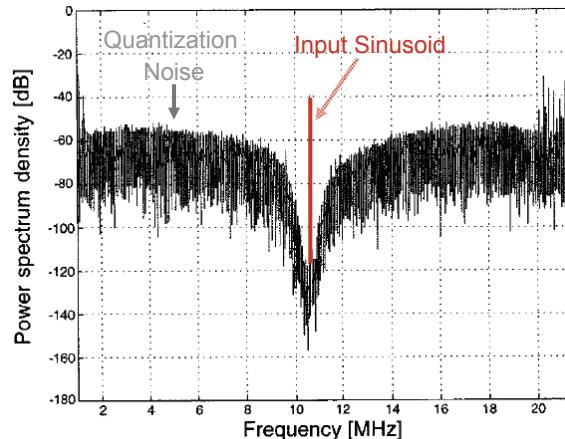
### Key Point:

NTF  $\rightarrow$  notch  
type  
shape

STF  $\rightarrow$  bandpass  
shape

Ref:

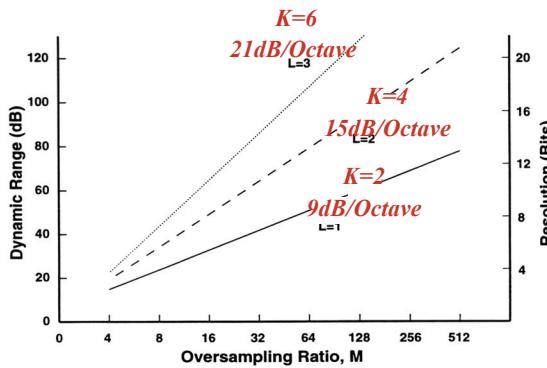
Paolo Cusinato, et. al. "A 3.3-V CMOS 10.7-MHz Sixth-Order Bandpass Modulator with 74-dB Dynamic Range", IEEE JSSCC, VOL. 36, NO. 4, APRIL 2001



## Bandpass $\Sigma\Delta$ Characteristics

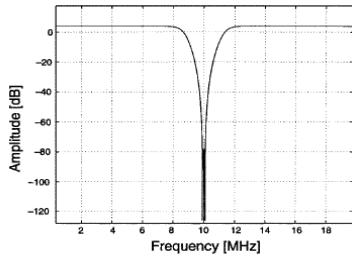
- Oversampling ratio defined as  $f_s/2B$  where  $B$  = signal bandwidth
- Typically, sampling frequency is chosen to be  $f_s=4xf_{center}$  where  $f_{center} \rightarrow$  bandpass filter center frequency
- STF has a bandpass shape while NTF has a notch or band-reject shape
- To achieve same resolution as lowpass, need twice as many integrators

### Bandpass $\Sigma\Delta$ Modulator Dynamic Range As a Function of Modulator Order (K)

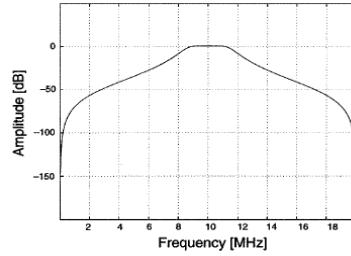


- Bandpass  $\Sigma\Delta$  resolution for order K is the same as lowpass  $\Sigma\Delta$  resolution with order L = K/2

## Example: Sixth-Order Bandpass $\Sigma\Delta$ Modulator



Simulated noise transfer function



Simulated signal transfer function

Ref:

Paolo Cusinato, et. al, "A 3.3-V CMOS 10.7-MHz Sixth-Order Bandpass Modulator with 74-dB Dynamic Range ", IEEE JSSCC, VOL. 36, NO. 4, APRIL 2001

## Example: Sixth-Order Bandpass $\Sigma\Delta$ Modulator

### Features & Measured Performance

Analog input full-scale	4.4V (differential)
Sampling frequency ( $f_s$ )	42.8MHz $\leftarrow f_s = 4x f_{center}$
Center frequency ( $f_0$ )	10.7MHz
Signal bandwidth	200kHz $\leftarrow B$
OSR	107 $\leftarrow OSR = f_s / 2B$
Dynamic range	74dB (200kHz band) 88dB (9kHz band)
Peak SNDR	61dB
IMD (@ -15dB)	71dbc
Active die area	1mm <sup>2</sup>
Power supply	3.3V
Power consumption	76mW (adaptive biasing) 126mW (standard biasing)
Technology	0.35μm CMOS

Ref:

Paolo Cusinato, et. al, "A 3.3-V CMOS 10.7-MHz Sixth-Order Bandpass Modulator with 74-dB Dynamic Range ", IEEE JSSCC, VOL. 36, NO. 4, APRIL 2001

## Summary Oversampled ADCs

- Noise shaping utilized to reduce baseband quantization noise power
- Reduced precision requirement for analog building blocks compared to Nyquist rate converters
- Relaxed transition band requirements for analog anti-aliasing filters due to oversampling
- Takes advantage of low cost, low power digital filtering
- Speed is traded for resolution
- Typically used for lower frequency applications compared to Nyquist rate ADCs

## ADC Figures of Merit

- Objective: Want to compare performance of different ADCs
- Can use FOM to combine several performance metrics to get one single number
- What are reasonable FOM for ADCs?

# ADC Figures of Merit

$$FOM_1 = f_s \cdot 2^{ENOB}$$

- This FOM suggests that adding a bit to an ADC is just as hard as doubling its bandwidth
- Is this a good assumption?

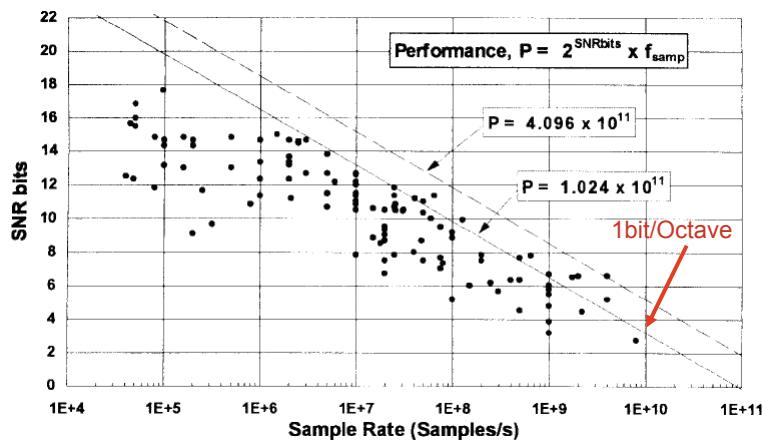
Ref: R.H. Walden, "Analog-to-digital converter survey and analysis," *IEEE J. Selected Areas Comm.*, April 1999

EECS 247- Lecture 26

Bandpass Oversampled ADCs- Systems

© 2009 Page 11

## Survey Data



Ref: R.H. Walden, "Analog-to-digital converter survey and analysis," *IEEE J. Selected Areas Comm.*, April 1999

EECS 247- Lecture 26

Bandpass Oversampled ADCs- Systems

© 2009 Page 12

## ADC Figures of Merit

$$FOM_2 = \frac{Power}{f_s \cdot 2^{ENOB}} \quad [J/conv]$$

- Sometimes inverse of this metric is used
- In typical circuits power  $\sim$  speed,  $FOM_2$  captures this tradeoff correctly
- How about power vs. ENOB?
  - One more bit 2x in power?

Ref: R.H. Walden, "Analog-to-digital converter survey and analysis," *IEEE J. Selected Areas Comm.*, April 1999

## ADC Figures of Merit

- One more bit means...
  - 6dB SNR, 4x less noise power, 4x larger C
  - Power  $\sim Gm \sim C$  increases **4x**
- Even worse: Flash ADC
  - Extra bit means 2x number of comparators
  - Each of them needs double precision
  - Transistor area 4x, Current 4x to keep same current density
  - Net result: Power increases **8x**

## ADC Figures of Merit

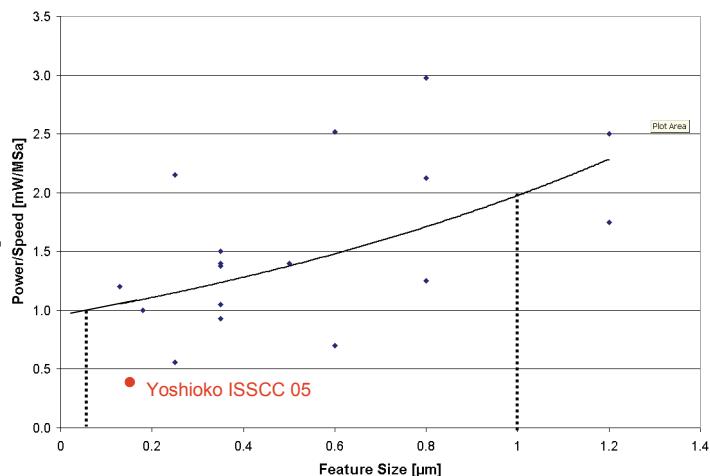
- FOM<sub>2</sub> seems not quite appropriate, but somehow still standard in literature, papers
- "Tends to work" because:
  - Not all power in an ADC is "noise limited"
  - E.g. Digital power, biasing circuits, etc.
- Avoid comparing different resolution ADCs using FOM<sub>2</sub>!

## ADC Figures of Merit

$$FOM_3 = \frac{Power}{Speed}$$

- Compare only power of ADCs with approximately same ENOB
- Useful numbers:
  - 10b (~9 ENOB) ADCs: 1 mW/MSample/sec  
Note the ISSCC 05 example: 0.33mW/MS/sec!
  - 12b (~11 ENOB) ADCs: 4 mW/MSample/sec

## 10-Bit ADC Power/Speed

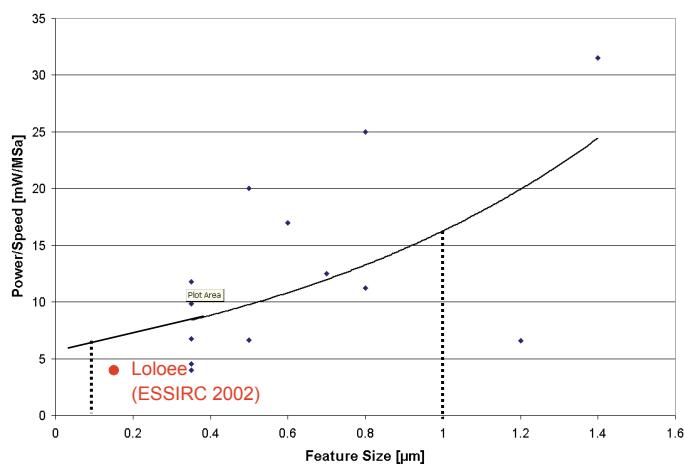


EECS 247- Lecture 26

Bandpass Oversampled ADCs- Systems

© 2009 Page 17

## 12-Bit ADC Power/Speed



EECS 247- Lecture 26

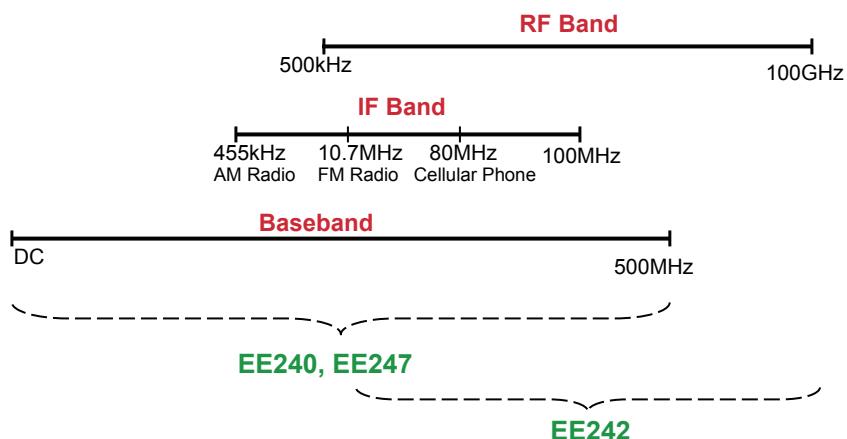
Bandpass Oversampled ADCs- Systems

© 2009 Page 18

## Material Covered in EE247

- Filters
  - Continuous-time filters
    - Biquads & ladder type filters
    - Opamp-RC, Opamp-MOSFET-C, gm-C filters
    - Automatic frequency tuning
  - Switched capacitor (SC) filters
- Data Converters
  - D/A converter architectures
  - A/D converter
    - Nyquist rate ADC- Flash, Interpolating & Folding, Pipeline ADCs,....
    - Self-calibration techniques
    - Oversampled converters

## E.E. Circuit Courses vs. Frequency Range

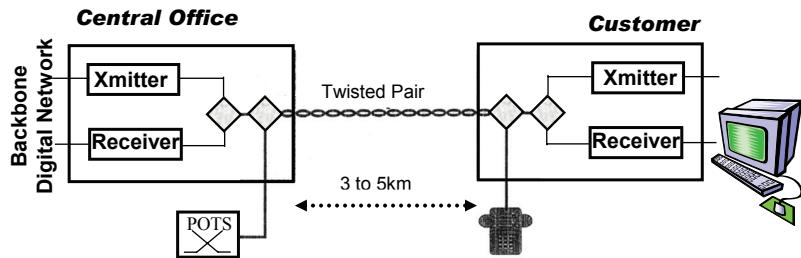


## Systems Including Analog-Digital Interface Circuitry (Not Included in Final Exam)

- Wireline communications
  - Telephone related (DSL, ISDN, CODEC)
  - Television circuitry (Cable modems, TV tuners...)
  - Ethernet (10/1Gigabit, 10/100BaseT...)
- Wireless
  - Cellular telephone (CDMA, Analog, GSM....)
  - Wireless LAN (Blue tooth, 802.11a/b/g.....)
  - Radio (analog & digital), Television
- Disk drives
- Fiber-optic systems

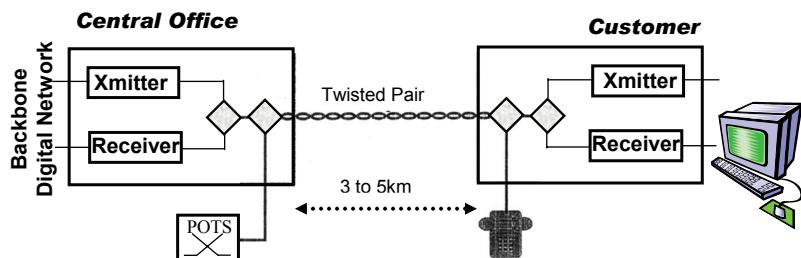
## Wireline Communications Telephone Based

## Data Transmission Over Existing Twisted-Pair Phone Lines



- Data transmitted over existing phone lines (originally meant to carry 4kHz voice grade signal) covering distances close to 3.5 miles
  - Voice-band MODEMs (up to 56Kb/s)
  - ISDN (160Kb/s)
  - HDSL, SDSL,.....
  - ADSL (up to 8Mb/s)

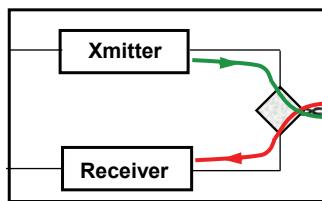
## Data Transmission Over Twisted-Pair Phone Lines ISDN (U-Interface) Transceiver



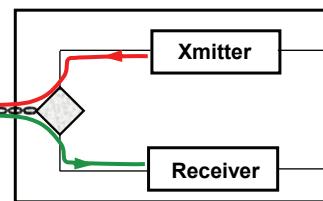
- Full duplex transmission (RX & TX signals sent simultaneously)
- 160kbit/sec baseband data (80kHz signal bandwidth)
- Standardized line code 2B1Q (4 level code 3:1:-1:-3)
- Max. desired loop coverage 18kft (~36dB signal attenuation)
- Final required BER (bit-error-rate)  $10^{-7}$  → (min. SNDR=27dB)

## ISDN (U-Interface) Transceiver Echo Problem

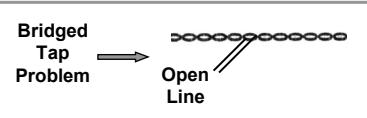
### Central Office



### Customer

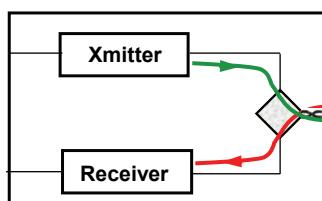


- Transformer coupling to line
  - For a perfectly matched system → no leakage of TX signal into RX path
  - Unfortunately, system has poor matching + complicating factor of bridged-taps

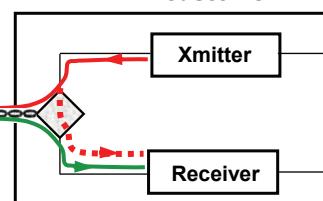


## ISDN (U-Interface) Transceiver Echo Problem

### Central Office

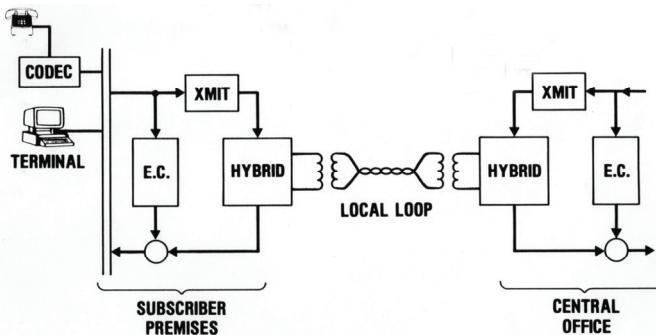


### Customer



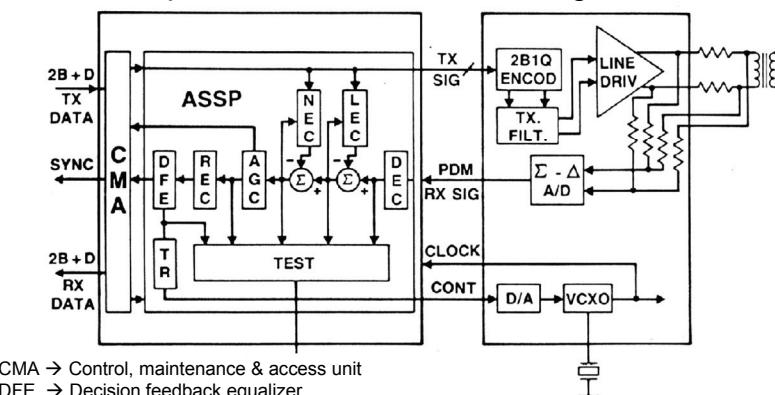
- System full duplex transmission → RX & TX signals sent simultaneous (& at the same frequency band)
  - Leakage of TX signal to RX path (echo)
  - Worst case → echo could be **30dB** higher compared to the received signal!!

## ISDN (U-Interface) Transceiver Echo Cancellation



- Echo cancellation performed in the digital domain
    - Typically echo cancellation performed by transversal adaptive digital filter
    - Any non-linearity incurred by the analog circuitry makes echo canceller significantly more complex
- Desirable to have high linearity analog circuitry (75dB range)

## Simplified Transceiver Block Diagram



CMA → Control, maintenance & access unit

DFE → Decision feedback equalizer

REC → Reconstruction filter

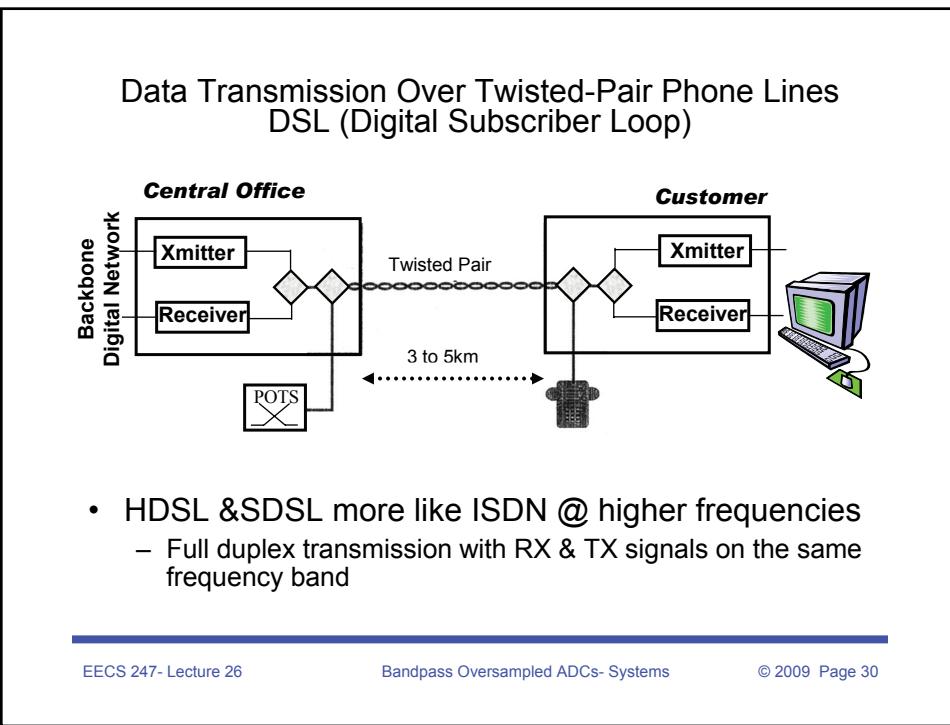
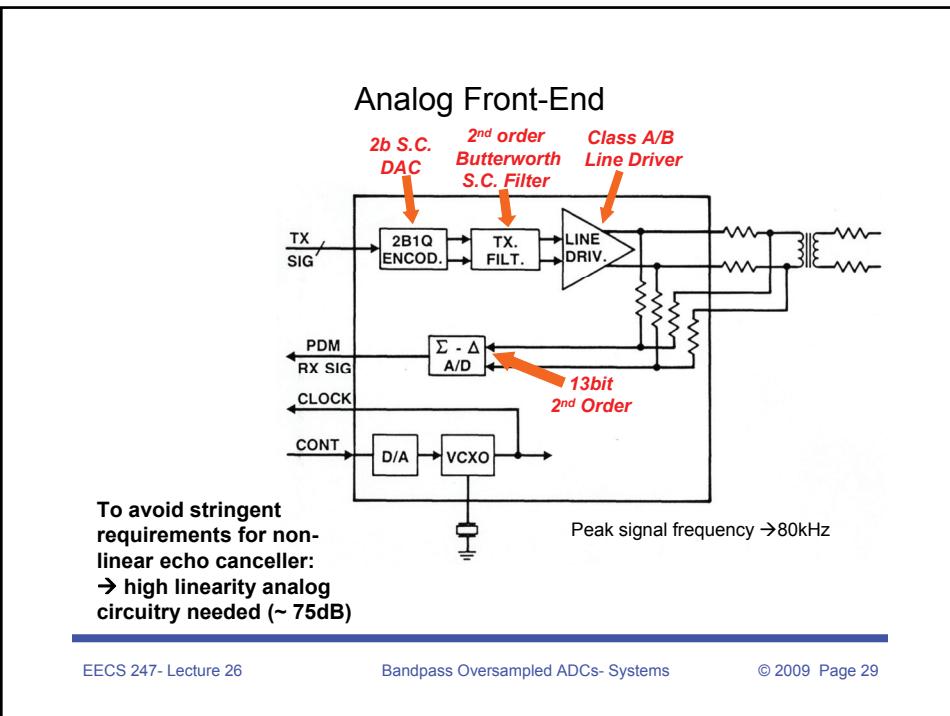
AGC → Automatic Gain Control

TEST → Test logic

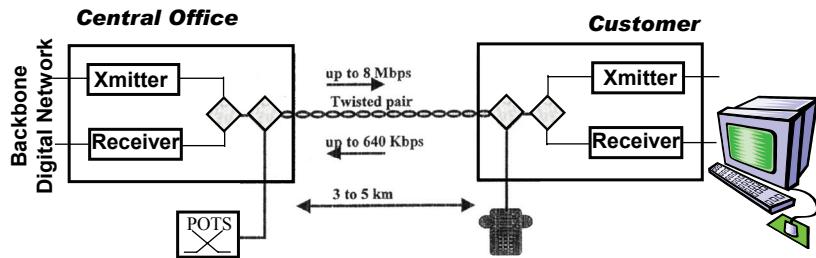
DEC → Decimation filter

LEC & NEC → Linear/non-linear echo-canceller

Ref: H. Khorramabadi, et. al "An ANSI standard ISDN transceiver chip set," *IEEE International Solid-State Circuits Conference*, vol. XXXII, pp. 256 - 257, February 1989



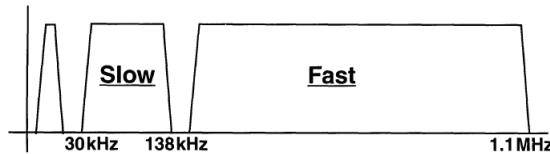
## Data Transmission Over Twisted-Pair Phone Lines ADSL (Asymmetric Digital Subscriber Loop)



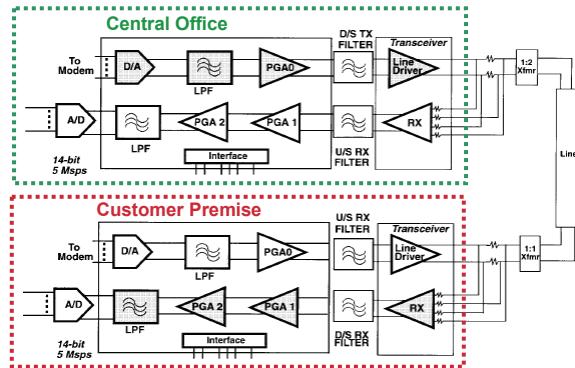
- In USA mostly ADSL → FDM (frequency division multiplex)
  - Signal from CO to customer on a different frequency band compared to customer to CO
    - Echo cancellation can be performed by simple filtering
  - Data rates up to 8Mbps (much higher compared to ISDN)

## ADSL Signal Characteristics

- Main difference compared to ISDN: TX & RX signals on different frequency bands
  - Downstream (*fast*, from CO to customer) 138kHz to 1.1MHz
  - Upstream (*slow*, from customer to CO) 30kHz to 138kHz
    - Echo cancellation much easier
- More severe signal attenuation at high frequencies (1MHz DSL v.s. 80kHz ISDN)

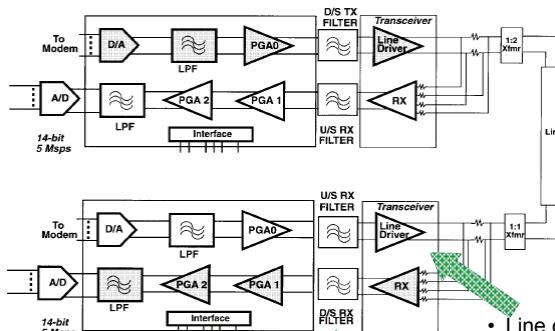


## Typical ADSL Analog Front-End



- ADC 16/14b with 14bit linearity, pipelined with auto. calibration @ 5Ms/s
  - DAC 16/14b with 14bit linearity, with auto. calibration
  - On-chip filters 3<sup>rd</sup> to 4<sup>th</sup> order LPF with  $f_c$  1.1MHz for downstream and 138kHz upstream (typically continuous-time type filters with on-chip frequency tuning)
- Ref: D.S. Langford, et al, "A BiCMOS Analog Front-End Circuit for an FDM-Based ADSL System," *IEEE Journal of Solid State Circuits*, Vol. 33, No. 9, pp. 1383-1393, Dec. 1998.

## Typical ADSL Analog Front-End



- Note: Band selection filters are off-chip due to stringent noise requirements (3nV/rtHz)
  - Discrete LC type

• Line driver on a separate bipolar chip to achieve required high output signal levels with high power efficiency typically +/-12V supply

# Wireless Communication Circuits

---

EECS 247- Lecture 26

Bandpass Oversampled ADCs- Systems

© 2009 Page 35

## Wireless Circuits

- Differ from wired comm. circuits
  - Includes RF circuitry + IF circuitry + baseband circuits (three different frequency ranges)
  - Signal scenarios in wireless receivers more challenging
  - Requirement for received signal BER in the order of  $10^{-3}$  for voice-only → (min. SNR~9dB)

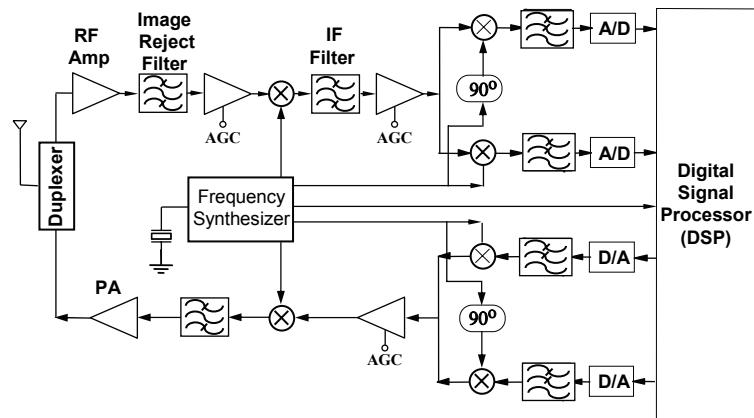
---

EECS 247- Lecture 26

Bandpass Oversampled ADCs- Systems

© 2009 Page 36

## Typical Cellular Phone Block Diagram

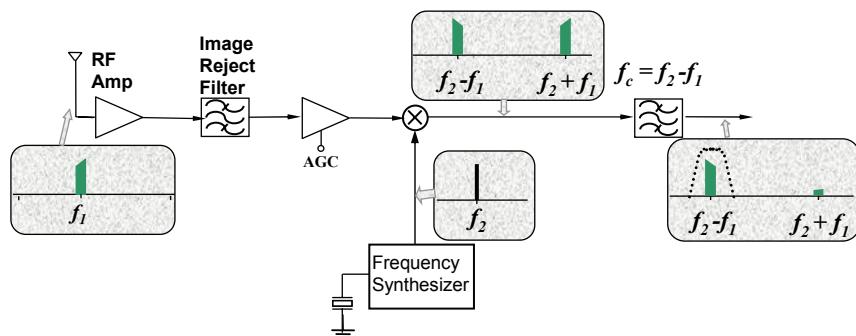


EECS 247- Lecture 26

Bandpass Oversampled ADCs- Systems

© 2009 Page 37

## Superheterodyne Receiver



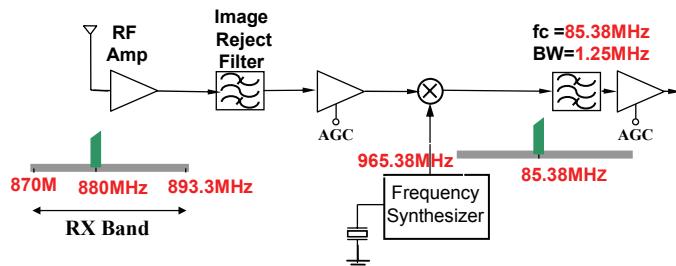
- One or more intermediate frequency (IF)
- Periodic signal at a frequency equal to the desired RX signal + or – IF frequency is provided by a Local Oscillator
- RX signal is frequency shifted to a fixed frequency (IF filter center frequency)

EECS 247- Lecture 26

Bandpass Oversampled ADCs- Systems

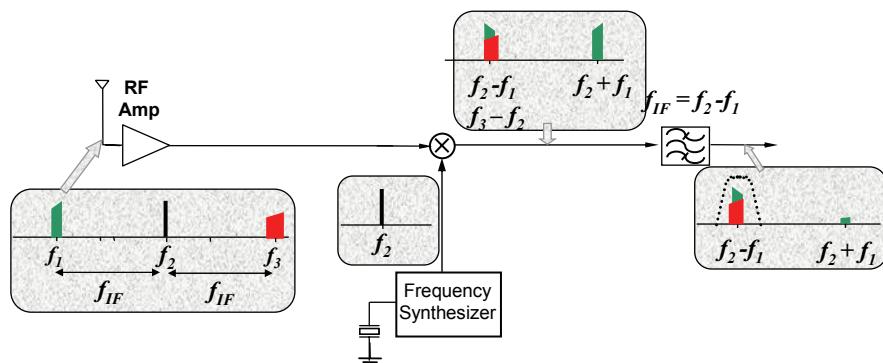
© 2009 Page 38

## RF Superheterodyne Receiver Example: CDMA Receiver



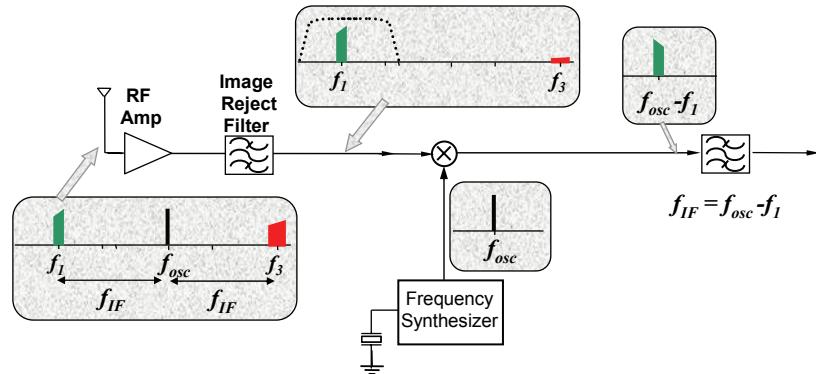
- Received frequency is mixed down to a fixed IF frequency and then filtered with a bandpass filter

## Why Image Reject Filter?



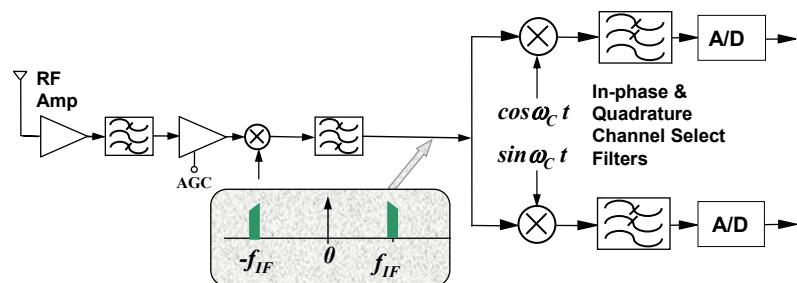
- Any signal @ the image frequency of the RX signal with respect to Osc. frequency will fall on the desired RX signal and cause impairment

## Why Image Reject Filter?



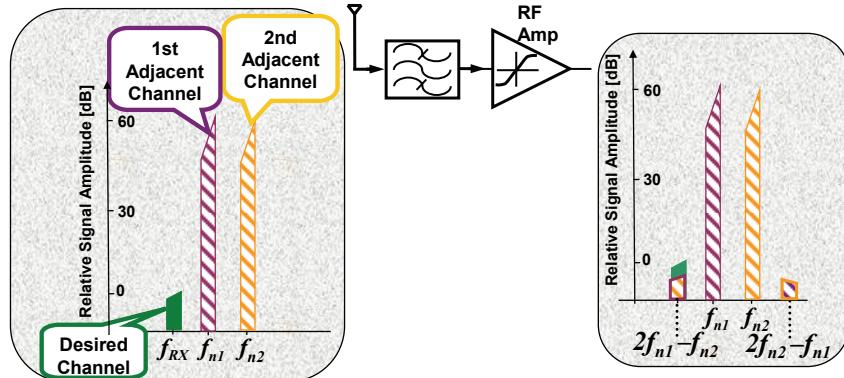
- Image reject filter attenuate signals out of the RX band
- Typically, image reject filters are ceramic or LC type filters

## Quadrature Downconversion



- In systems with phase or freq. modulation, since signal is not symmetric around  $f_{IF}$ , directly converting down to baseband corrupts the sidebands
  - Quadrature downconversion overcomes this problem
  - Thus requiring two sets of baseband filters & ADCs

## Effect of Adjacent Channels

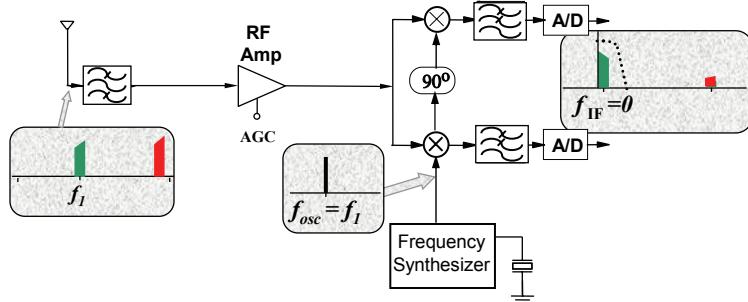


- Adjacent channels can be as much as **60dB** higher compared to the desired RX signal!
- Linearity of stages prior and including channel selection filters extremely important

## Effect of Adjacent Channels

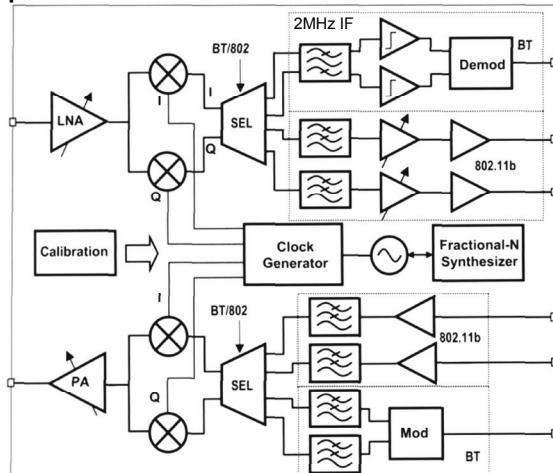
- Due to existence of large unwanted signals & limited dynamic range for the front-end circuitry:
  - Can not amplify the signal up front due to linearity issues
  - Need to allocate amplification/filtering specifications to RX blocks carefully
  - Can only amplify when unwanted signals are filtered adequately
  - System design critical with respect to tradeoffs affecting:
    - Gain
    - Linearity
    - Power dissipation
    - Chip area

## Homodyne (Direct to Baseband) Receivers



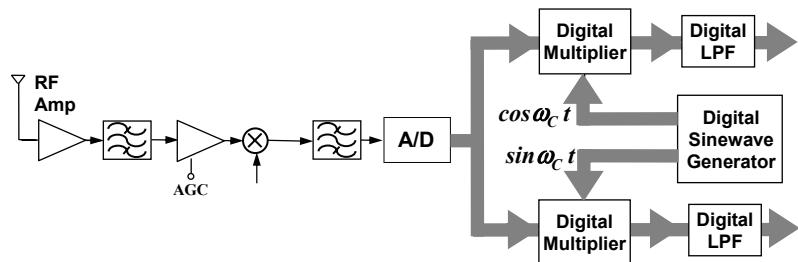
- No intermediate frequency, signal mixed directly down to baseband
- Almost all of the filtering performed at baseband
  - Higher levels of integration possible
  - Issue to be aware of:
    - Requirements for the baseband filters more stringent
    - Since the local oscillator frequency is exactly at the same freq. as the RX signal freq. → can cause major DC offsets & drive the receiver front-end into non-linear region

## Example: Wireless LAN 802.11b & Bluetooth



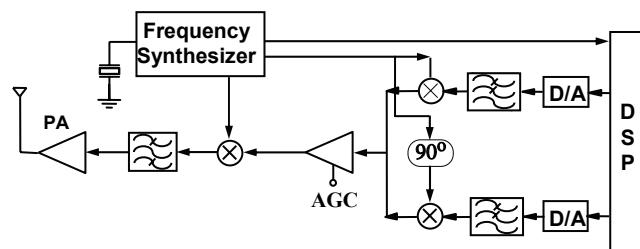
Ref: H. Darabi, et al, "A Dual Mode 802.11b/Bluetooth Radio in 0.35um CMOS," IEEE ISSCC, 2003 pp. 86-87.

## Digital IF Receiver (IF sampling)



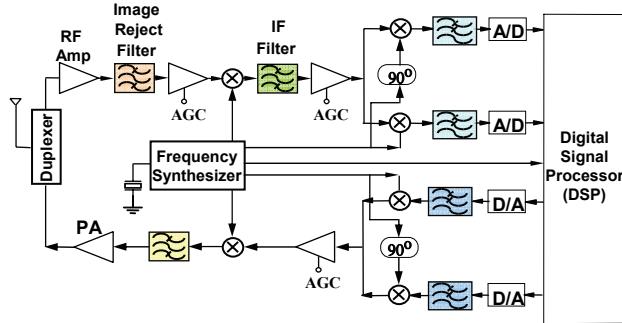
- IF signal is converted to digital → most of signal processing performed in the digital domain
- Performance requirement for ADC more demanding in terms of noise, linearity, and dynamic range!
- With advancements of ADCs could be the architecture of choice in the future

## Typical Wireless Transmitter



- Transmit signal shipped from DSP to the analog front-end in the form of I&Q signals
- Signal converted to analog form by D/A
- Lowpass filter provides signal shaping
- In-phase & Quad. Components combined and then mixed up to RF
- Power amplifier amplifies and provides the low-impedance output

## Analog Filters in Super-Heterodyne Wireless Transceivers



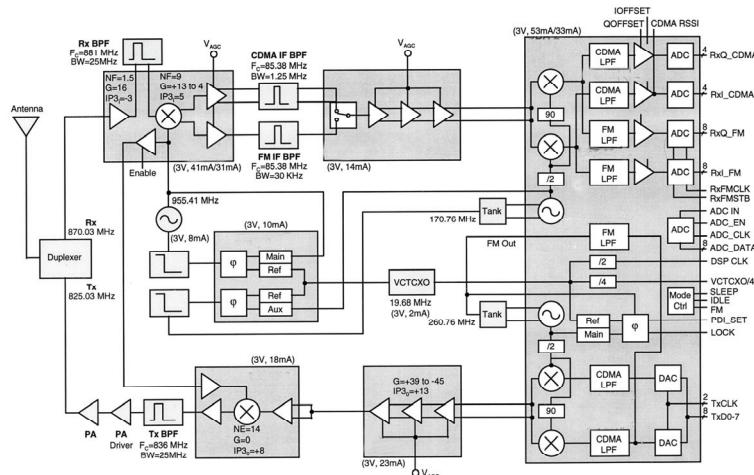
<u>Filters</u>	<u>Function</u>	<u>Type</u>
RF Filter	Image Rejection	Ceramic or LC
IF Filter	Channel selection	SAW
Base-band Filters	Channel Selection & Anti-aliasing for ADC	Integrated Cont.-Time or S.C.

EECS 247- Lecture 26

Bandpass Oversampled ADCs- Systems

© 2009 Page 49

## Example: Dual Mode CDMA (IS95)& Analog Cellular Phone



EECS 247- Lecture 26

Bandpass Oversampled ADCs- Systems

© 2009 Page 50

## Example: Dual Mode CDMA (IS95)& Analog Cellular Phone

- Typical baseband analog circuitry includes:
  - CDMA
    - 4bit flash type ADC clock rate 10MHz
    - 8bit segmented TX DAC clock rate 10MHz (shared with FM)
    - 7<sup>th</sup> order elliptic RX lowpass filter corner freq. 650kHz
    - 3<sup>rd</sup> order chebyshev TX lowpass filter corner freq. 650kHz
  - FM (analog)
    - 8bit successive approximation ADCs clock rate 360kHz
    - 5<sup>th</sup> order chebyshev RX lowpass filter corner frequency 14kHz
    - 3<sup>rd</sup> order butterworth TX lowpass filter corner frequency 27kHz

## Summary

- Examples of systems utilizing challenging analog to digital interface circuitry- in the area of wireline & wireless systems discussed
- Analog circuits still remain the interface → connecting the digital world to the real world!

## Acknowledgements

- The course notes for EE247 are based on numerous sources including:
  - Prof. P. Gray's EE290 course
  - Prof. B. Boser's EE247 course notes
  - Prof. B. Murmann's Nyquist ADC notes
  - Fall 2004 thru 2008 EE247 class feedback
  - Last but not least, Fall 2009 EE247 class
    - The instructor would like to thank the class of 2009 for their enthusiastic & active participation!