EC5.203 Communication Theory (3-1-0-4):

Lecture 10:

Analog Communication Techniques:

Superheterodyne Receiver

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References

- Chap. 3 (Madhow)

Recap:
FM Spectrum

FM spectrum

- Narrowband FM
  - Similar to DSB
  - Bandwidth = 2B (where B=message bandwidth)
- Wideband FM
  - Bandwidth dominated by max frequency deviation
- Carson's formula: adds the two components

Wideband FM

- Bandwidth is dominated by frequency deviation

$$\Delta f = k_f m(t)$$

- Frequency will swing between $\pm\Delta f_{\max}$ assuming equal positive and negative swings in message.

$$\Delta f_{\max} = k_f \max_t |m(t)|$$

- Bandwidth $B_{\mathrm{FM}} = 2\Delta f_{\max}$

Carson's rule

- Add up estimates for narrowband and wideband FM

$$B_{\mathrm{FM}} \approx 2B + 2\Delta f_{\max} = 2B(\beta + 1)$$

where $\beta = \Delta f_{\max}/B$ is the FM modulation index or the deviation ration.

Bandwidth of Angle Modulated Waveforms

- Prove that Angle Modulated Waveforms have infinite bandwidth theoretically!
- As a special case, derive narrowband FM expression and its bandwidth!
- Note that Angle modulation is non-linear but NBFM and NBPM are (incrementally) linear modulation schemes.

Ref: B.P.Lathi

FM spectrum for periodic messages

- Complex envelope is periodic for periodic messages $\rightarrow$ Fourier series
  - Spectrum of complex envelope is discrete with impulses at integer multiples of fundamental frequency
- Standard example: sinusoidal message
  - But approach is quite general
- Somewhat artifical since most messages (such as speech) are not periodic

(Approximate) FM spectrum

- The bandwidth of narrowband FM ($\beta < 1$) is 2B where B is the bandwidth of the signal $m(t)$.

Assumption $\theta(t)$ is small for narrowband FM! Not valid for general case.

- Add up estimates for narrowband and wideband FM

$$B_{\mathrm{FM}} \approx 2B + 2\Delta f_{\max} = 2B(\beta + 1)$$

where $\beta = \Delta f_{\max}/B$ is the FM modulation index or the deviation ration.

Exact FM spectrum for sinusoidal message

- Prove that FM spectrum for sinusoidal message is given by

$$U(f) = \sum_{n=-\infty}^{\infty} J_n(\beta)\delta(f - nf_m)$$

where $J_n(\beta)$ is the n^{th} order Bessel function given by

$$J_n(\beta) = \frac{1}{2\pi}\int_{-\pi}^{\pi} e^{j(\beta \sin x - nx)}\, dx$$ Complex-valued integral

$$= \frac{1}{\pi} \cos(\beta \sin x - nx)\, dx$$ Real Valued

Fractional power containment BW

- Parseval's theorem: Power = sum of magnitude of Fourier series coefficients

$$1 = |u(t)|^2 = \overline{|u(t)|^2} = \sum_{n=-\infty}^{\infty} J_n^2(\beta) = J_0^2(\beta) + 2\sum_{n=1}^{\infty} J_n^2(\beta)$$

- Fractional power containment bandwidth for fraction α is $2Kf_m$ with K given by

$$J_0^2(\beta) + 2\sum_{n=1}^{K} J_n^2(\beta) \geq \alpha$$

Features of Angle Modulated Non-linearities

- Exchanging signal power with bandwidth
  - Bandwidth for AM cannot be changed while it can be changed based on Δf.
  - SNR is roughly proportional to square of transmission signal bandwidth.
- Immunity of angle modulation to non-linearities.
  - Non-linearity does not affect FM signal while it does affect AM signal.(Already proved)
  - Amplitude changes do not affect the FM signal

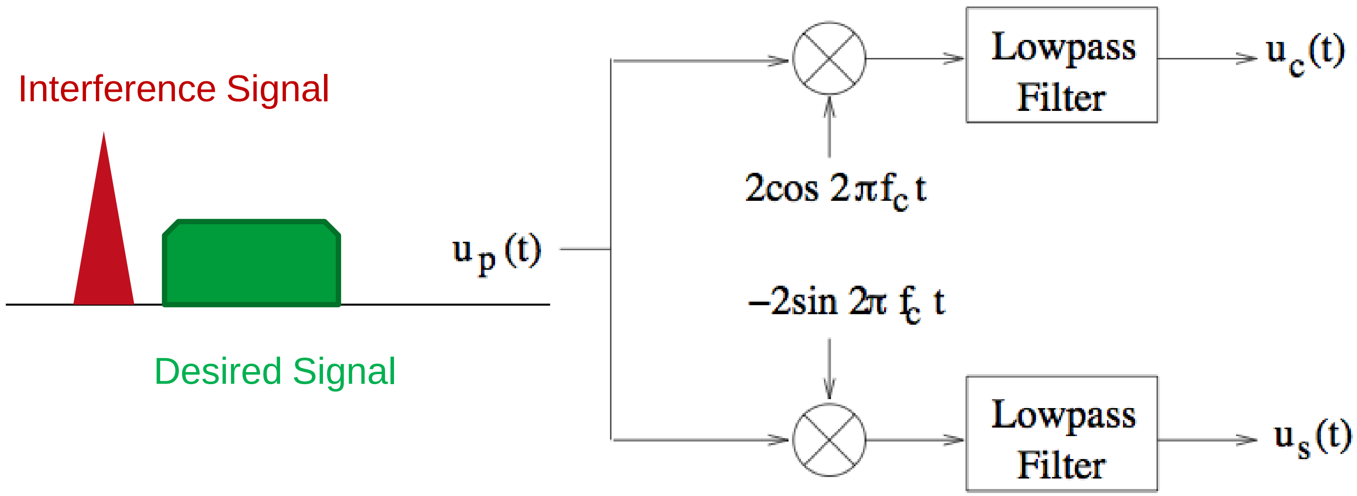
Ref: B.P.Lathi

Today's Class

Superheterodyne Receiver:

Applicable to AM/FM/PM

Downconversion: How it is done?



Downconversion
(passband to baseband)

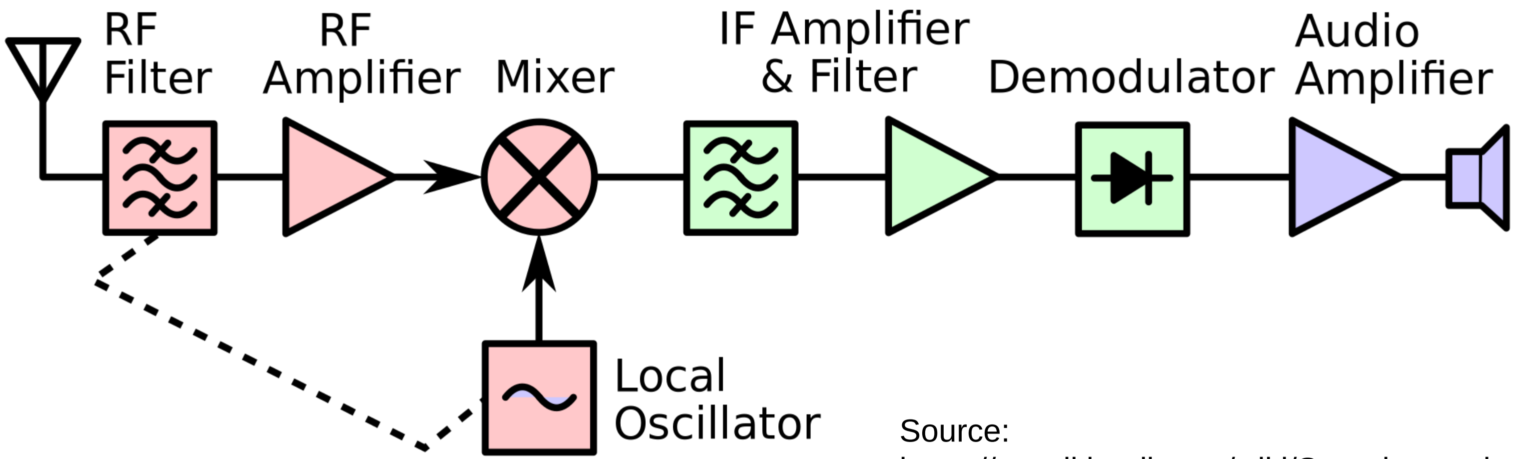
Not so simple as in the figure!

- Need to separate desired signal from interference
- Need to amplify the desired signal

Different Methods for Receiver

- Direct Conversion (Popular nowadays)
- Superheterodyne (Historical importance): Indirect conversion (convert to intermediate frequencies (IF) and then to baseband)

Superheterodyne Receiver



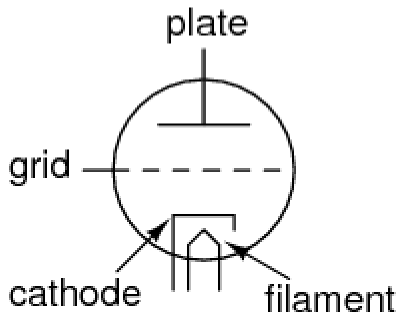
Source:
https://en.wikipedia.org/wiki/Superheterodyne_receiver

- Invented by Edwin Armstrong in 1918 during World War I.
- Superheterodyne is a contraction of *supersonic heterodyne*
  - supersonic indicates frequencies above the range of human hearing.
  - The word heterodyne is derived from the Greek roots hetero meaning *different*, and dyne meaning *power*.

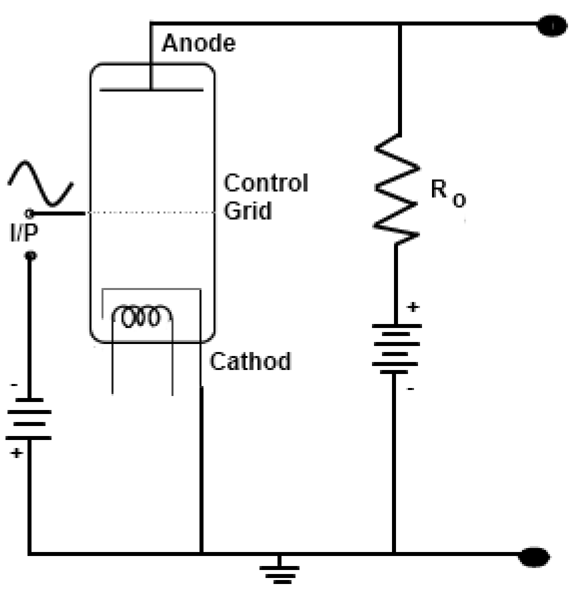
Motivation for Superheterodyne Receivers

- Difficulty in amplifying the received signal at frequecies beyond few MHz while using vacuum tube diodes and triodes.
- However higher frequencies are desired because of larger bandwidth and the smaller antennas required
- Still true: Difficult to provide large gains at high carrier frequencies. Gain is easier to provide at lower frequencies. Same is true with filtering.
- It becomes possible to optimize the processing at fixed IF in terms of filter design and amplification while permitting a tunable RF front end with more relaxed operation, which is important for design of radios that operate over a wide range of carrier frequencies
- Superhet architecture uses multiple stages of mixing to alleviate these problems.

Vacuum Tube Triode



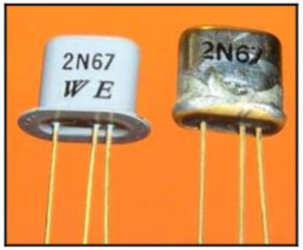
Symbol: http://www.allaboutcircuits.com/textbook/semiconductors/chpt-13/the-triode/



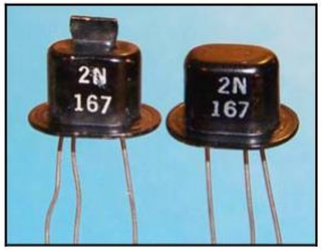
http://www.oneillselectronicmuseum.com/largephotos/tubes/yel/yel23.jpg

Amplifier Circuit: http://www.daenotes.com/electronics/devices-circuits/vacuum-tube-triode

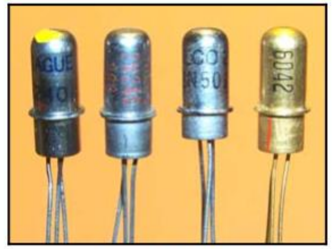
Transistors



2N67

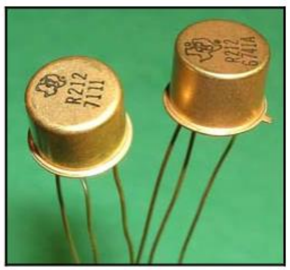


2N167



2N240/2N501

2N404



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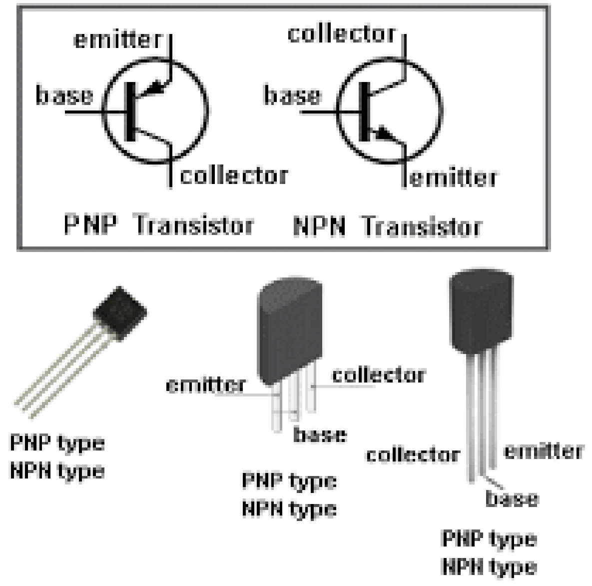


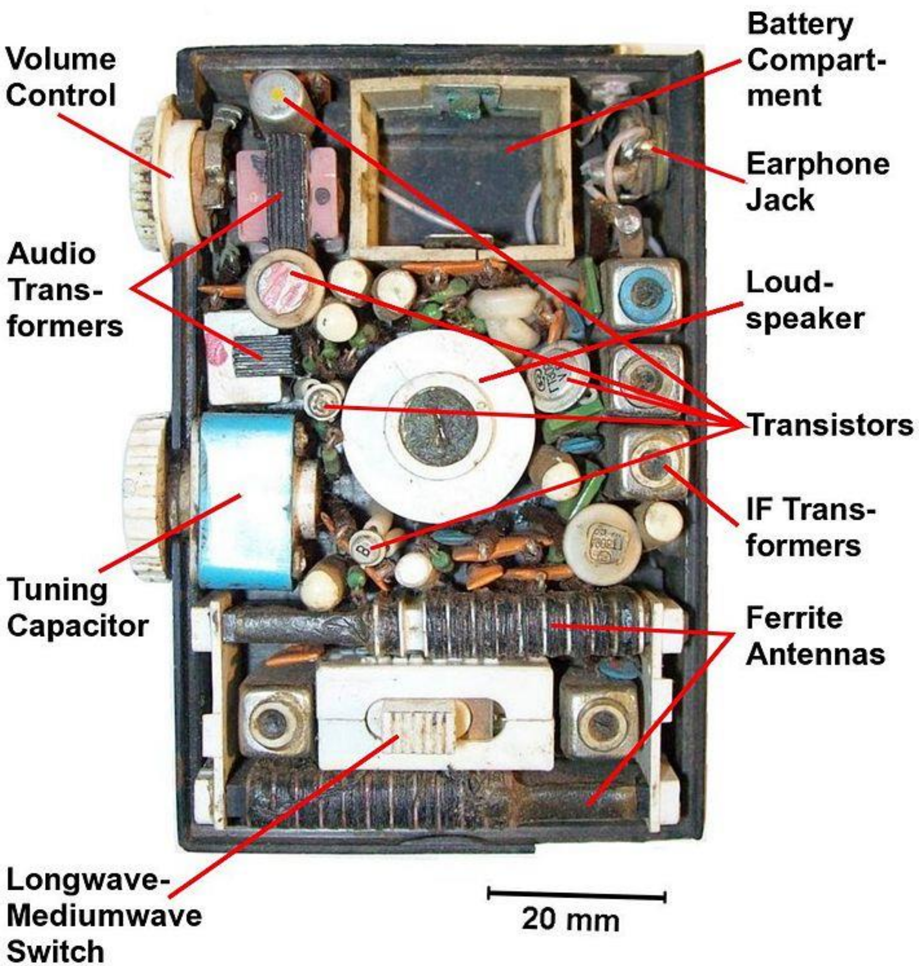
Old Germanium

Modern (Silicon)

http://ibm-1401.info/VintageGermaniumComputerTransistorsDavid%20Laws.pdf

http://www.talkingelectronics.com/projects/BasicElectronics-1A/BasicElectronics-1A_Page2.html

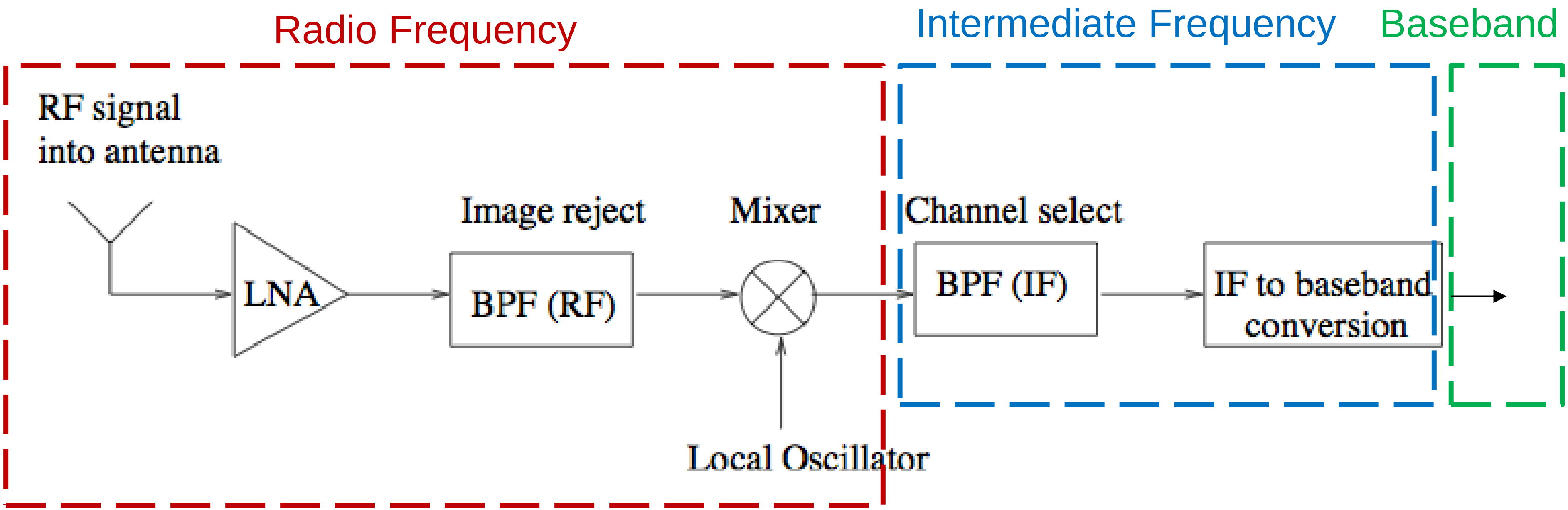
Example of Superheterodyne Transistor Receiver



Pocket transistor radio, late 1960s to 1970s, with 5 germanium transistors, that received long wave and medium wave (AM broadcast) bands. View with back open, showing parts. Powered by 2 button cells supplying 3V

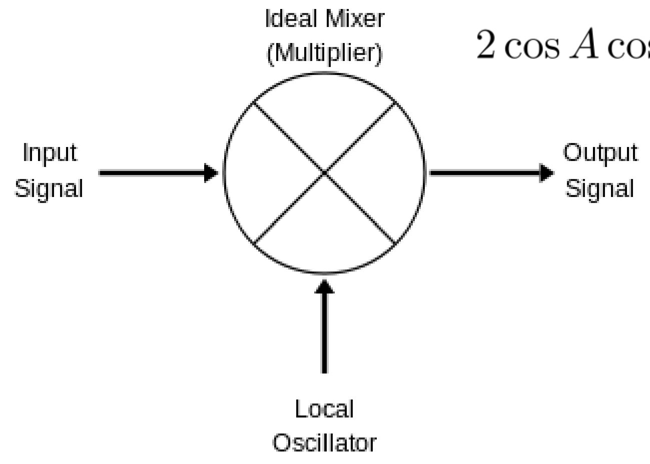
By Pocket_radio_open.jpg: Ulfbastelderivative work: Chetvorno (talk) - Pocket_radio_open.jpg, Public Domain, https://commons.wikimedia.org/w/index.php?curid=12819355

Superheterodyne receiver: *Principle*



- Sloppy RF filtering at the RF
- Careful processing at fixed IF: IF bandpass filter and amplifier provide most of the gain and narrowband filtering for the radio.
- RF front end often tunable (e.g., multiple bands in WiFi and cellular, multiple stations in AM or FM)

Mixer



$$2\cos A \cos B = \cos(A - B) + \cos(A + B)$$

https://en.wikipedia.org/wiki/Frequency_mixer

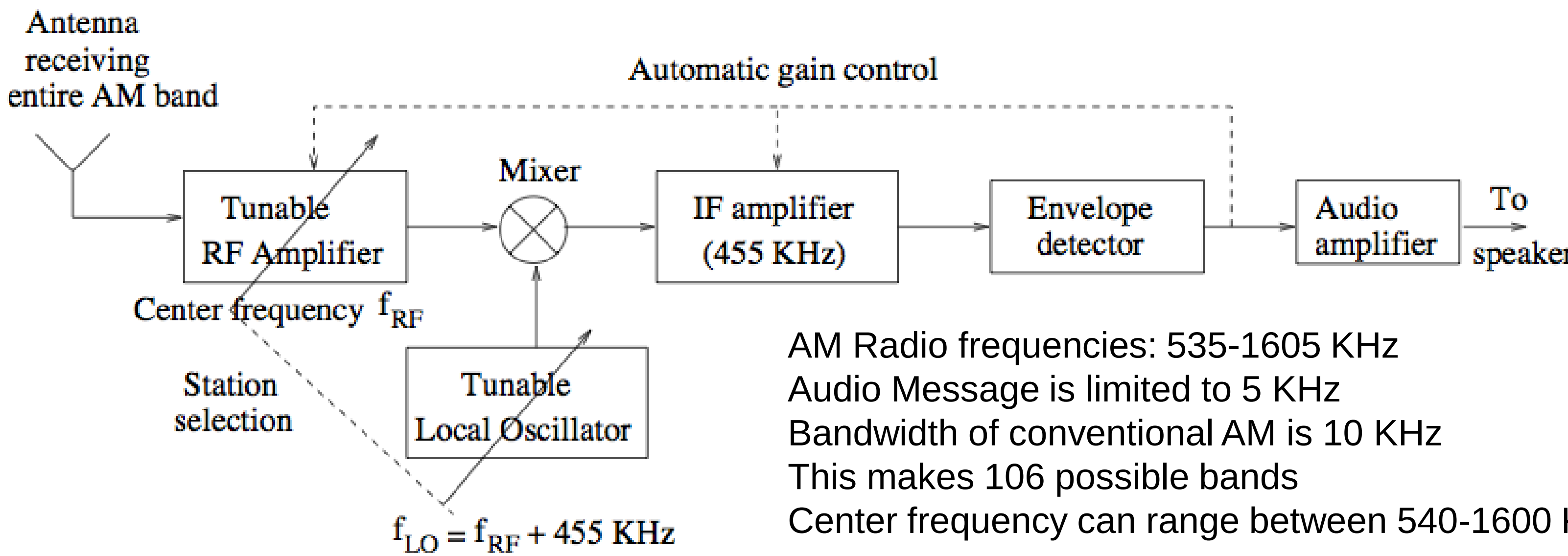
- In electronics, a mixer or frequency mixer is a nonlinear electrical circuit that creates new frequencies from two signals applied to it. In its most common application, two signals at frequencies f_1 and f_2 are applied to a mixer and it produces new signal at the sum $f_1 + f_2$ and difference $|f_1 - f_2|$ of the original frequencies called heterodynes.

- Nonlinear electronic components that are used as mixers include diodes, transistors biased near cutoff,

Mixer: Use of Non-linearity

$$\cos(2\pi f_1 t) + \cos(2\pi f_2 t) \longrightarrow \boxed{y(t) = x(t) + x^2(t)} \longrightarrow z(t)?$$

Example: superhet for AM radio

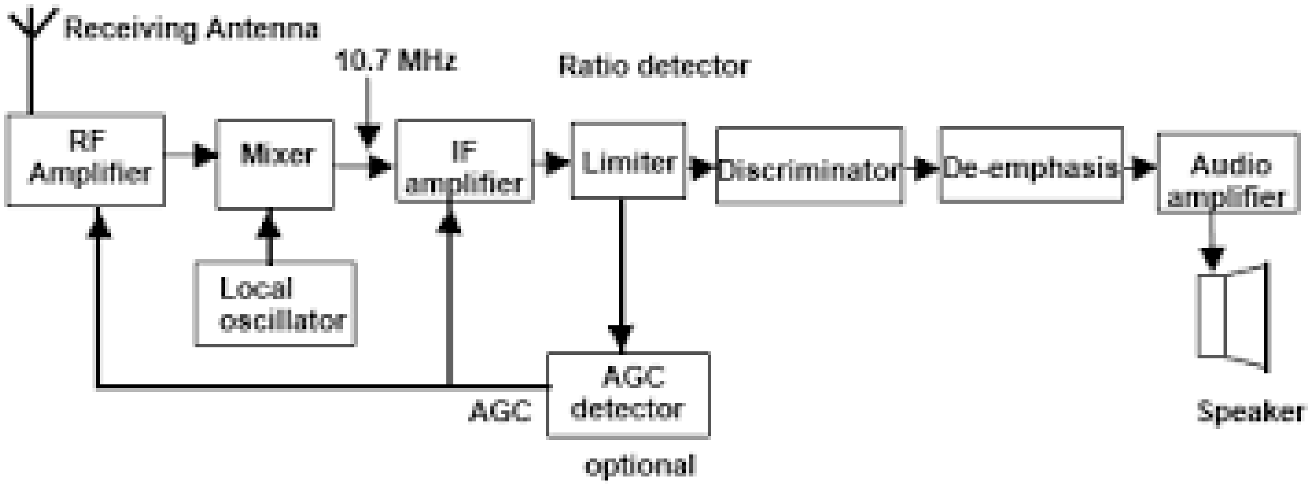


AM Radio frequencies: 535-1605 KHz
Audio Message is limited to 5 KHz
Bandwidth of conventional AM is 10 KHz
This makes 106 possible bands
Center frequency can range between 540-1600 KHz

- Two possibilities for LO frequency: Given IF, how to set LO frequency?
- Example for AM radio: RF freq. ranges from 540 to 1600 KHz
  - $f_{\mathrm{IF}} = 455$ KHz
  - $f_{\mathrm{LO}} = f_{\mathrm{RF}} + f_{\mathrm{IF}} \rightarrow$ LO freq. ranges from 995 to 2055 KHz (less variation in tuning range) ~ 2
  - $f_{\mathrm{LO}} = f_{\mathrm{RF}} - f_{\mathrm{IF}} \rightarrow$ LO freq. ranges from 85 to 1145 KHz (huge variation in tuning range) > 10

Example: superhet for FM radio

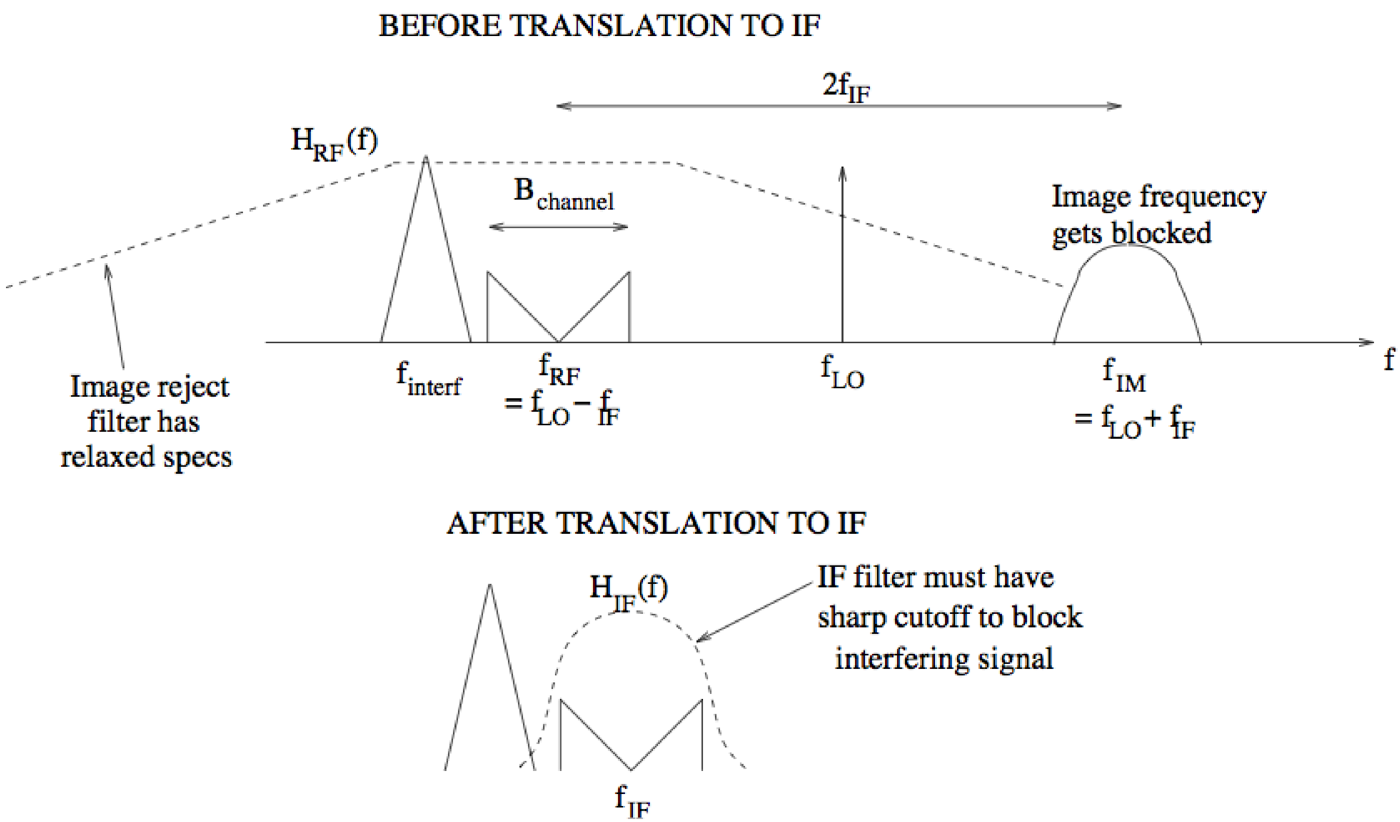
http://www.daenotes.com/electronics/communication-system/superheterodyne-fm-receiver



FM Radio frequencies: 88-108 MHz
Bandwidth of 150 KHz + 25 KHz guard band
200KHz spacing makes 100 stations
Center frequency assigned starting at 88.1 MHz

- What frequency should we choose for LO?

Superhet: freq domain operations



- Both $f_{\mathrm{LO}} - f_{\mathrm{IF}}$ and $f_{\mathrm{LO}} + f_{\mathrm{IF}}$ lead to an IF component $\rightarrow$ one of these is the undesired image frequency must be filtered out by RF front end.
- The IF filter filters out interference from adjacent channels.
- Sloppy requirement for RF but tight requirement for IF.

Disadvantages of SHR

- Issue of image frequency!
- Need of extra IF stage.
- There is a trade-off between rejecting image frequency and rejecting interference signal while choosing IF. This may necessitate multiple IF stages.
- Cannot use IC implementation and has to use bulky and costly filters such as surface-acoustic-wave (SAW).

Direct Conversion Receiver

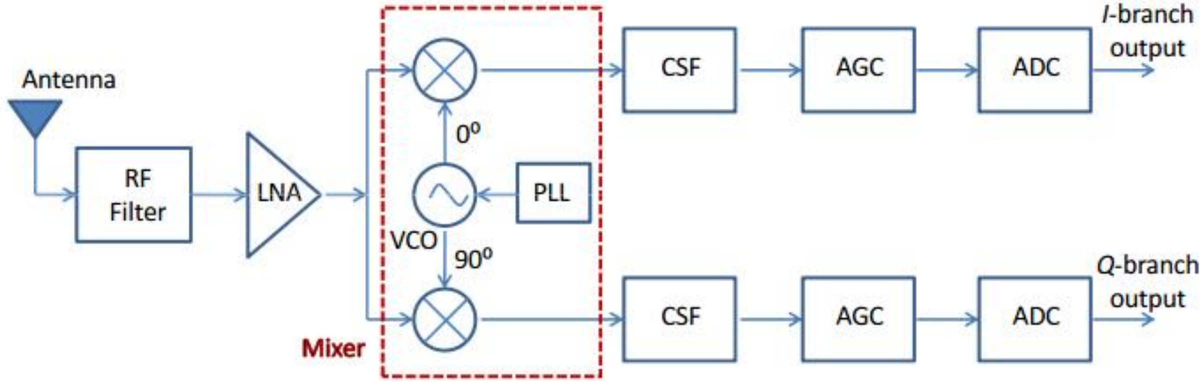


Figure 3.2. Typical RF front end of a direct conversion receiver. The components of the analog front end: wideband antenna, RF filter, low noise amplifier (LNA), voltage controlled oscillator (VCO), phase locked loop (PLL), channel select filter (CSF), automatic gain control (AGC), and analog-to-digital converter (ADC).

Source: Sachin Chaudhari, PhD Thesis; "Sensing for Cognitive Radios: Algorithms, Performance, and Limitations", Aalto University School of Electrical Engineering, Finland, 2012

- Direct conversion (*zero IF* or *homodyne* or *synchrodyne*, i.e., mixing down to baseband)
- Advantages: No image frequency, No IF stage, Cost benefit, Use of IC for compactness, Use of microprocessors for baseband processing of signal such as filtering.
- *Obvious thing to do*!

Disadvantages of DCR

- To match the performance of the superheterodyne receiver, a number of the functions normally addressed by the IF stage must be accomplished at baseband.
- Inability to implement envelope detection of AM signals. Therefore use of PLL is needed!
- Suffer from LO leakage to mixer input $\rightarrow$ DC component that can swamp later circuit components.
- Other issues such as Frequency offset, IQ imbalance, Narrowband interference.

Receiver for mmWave communication?

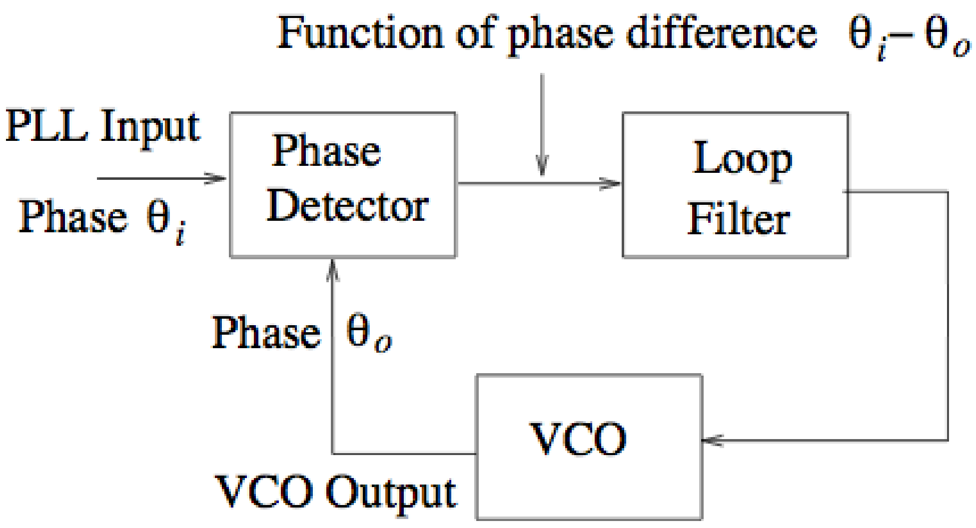
- Currently we are using mostly frequencies less than 5 GHz for communication
  - WLAN is using frequencies 2.4 and 5 GHz.
  - Cellular communication is using 900 and 1800 MHz bands.
- For the evergrowing need, we are looking at using frequencies much beyond 5 GHz (mmWave communication).
- For example, 60 GHz of carrier frequency can give us bandwidth of 5GHz.
- However direct receiver conversion is still a challenge there.
- Superheterodyne principle can be used with IF upto 5 GHz.

Phase Locked Loop (PLL)

PLL intro

- Legacy applications in analog communication and analog front-end of digital communication
  - FM demodulation
  - Carrier synchronization
- Key application in communication today: LO frequency synthesis
- Canonical structure for using feedback for continuous tracking

High-level view of PLL



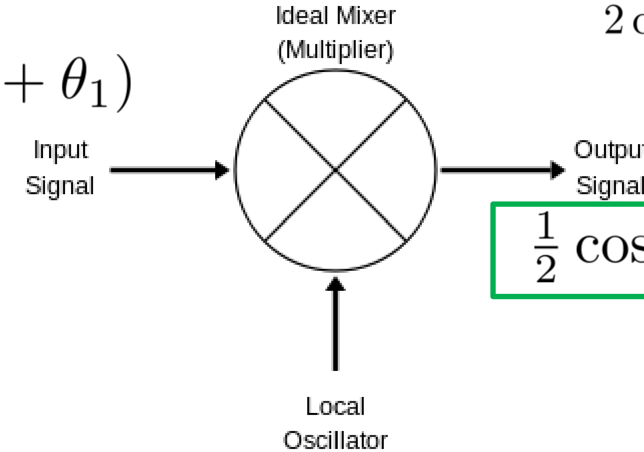
- Aim is to lock on the phase of the PLL input
- Phase detector compares input phase with locally generated phase at the VCO output
- Phase detector output is smoothed through loop filter and fed back to VCO input
  - If VCO output is ahead of the input phase, then retard the VCO phase
  - If VCO output is behind of the output phase, then advance VCO phase

Mixer as Phase Detector

Mixers can extract phase differences

$$2\cos A \cos B = \cos(A-B) + \cos(A+B)$$

$$\cos(2\pi f_c t + \theta_1)$$



$$\boxed{\frac{1}{2}\cos(\theta_1 - \theta_2)} + \cancel{\frac{1}{2}\cos(4\pi f_c t + \theta_1 + \theta_2)}$$

$$\cos(2\pi f_c t + \theta_2)$$

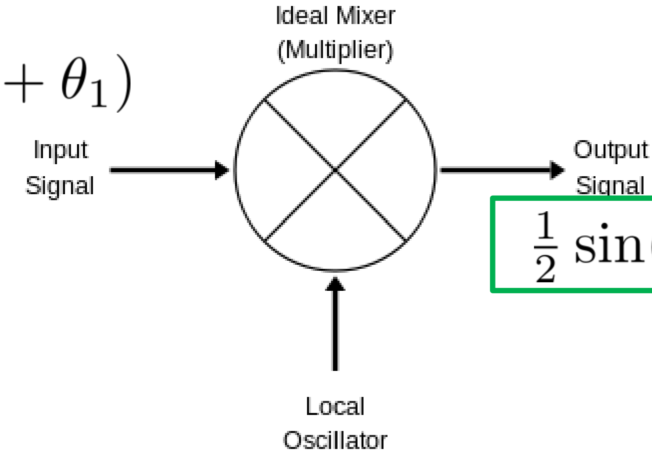
Phase lock condition: The term $\cos(\theta_1 - \theta_2) = 0$, i.e., $\theta_1 - \theta_2 = \pi/2$

For a natural phase lock condition of $\theta_1 - \theta_0 = 0$, change one of the sinusoids to sine wave.

Mixers can extract phase differences

$$-2\cos A \sin B = \sin(A-B) - \sin(A+B)$$

$$\cos(2\pi f_c t + \theta_1)$$

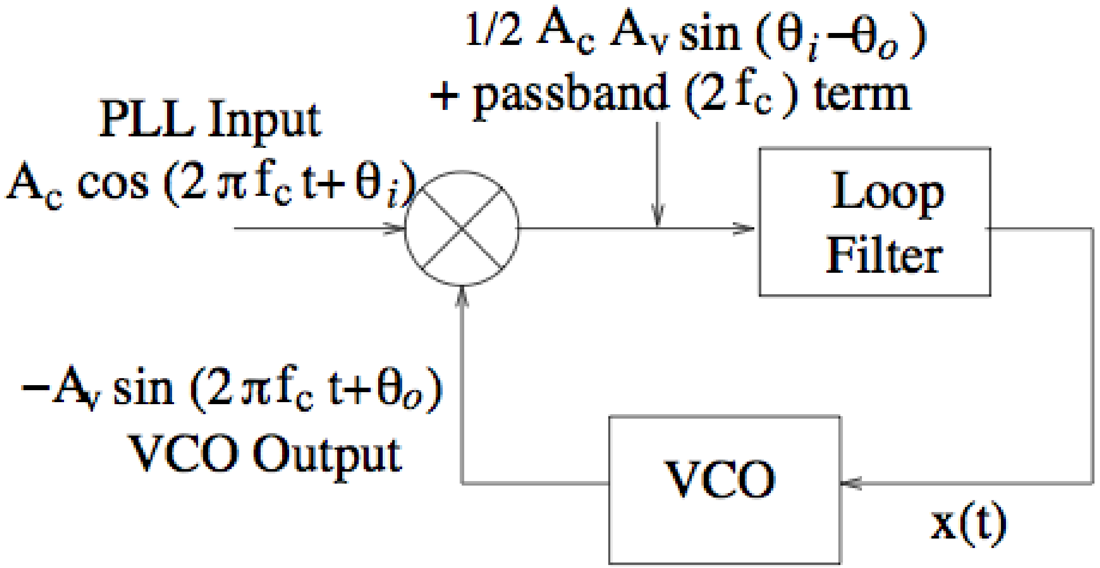


$$\boxed{\frac{1}{2}\sin(\theta_1 - \theta_2)} - \cancel{\frac{1}{2}\sin(4\pi f_c t + \theta_1 + \theta_2)}$$

$$-\sin(2\pi f_c t + \theta_2)$$

Phase lock condition: The term $\sin(\theta_1 - \theta_2) = 0$, i.e., $\theta_1 - \theta_2 = 0$

Mixer-based phase detector



- With this convention, the mixer output is given by

$$- A_c A_v \cos(2\pi f_c t + \theta_i(t)) \sin(2\pi f_c t + \theta_o(t))$$
$$= \frac{A_c A_v}{2} \sin(\theta_i(t) - \theta_o(t)) - \frac{A_c A_v}{2} \sin(4\,\pi f_c t + \theta_i(t) + \theta_o(t))$$

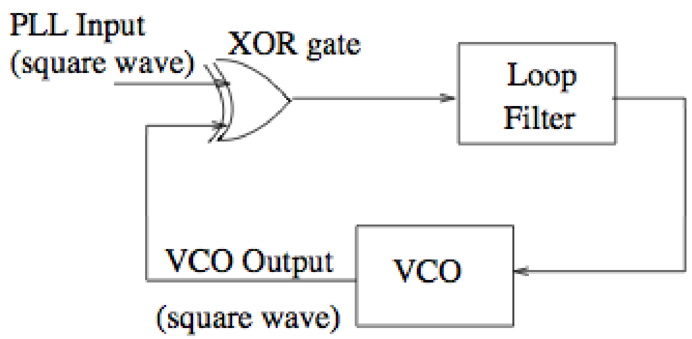
Phase difference term driving feedback loop

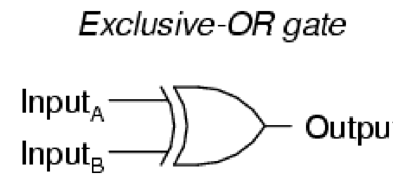
Double frequency term (filtered out)

Mixed signal phase detection

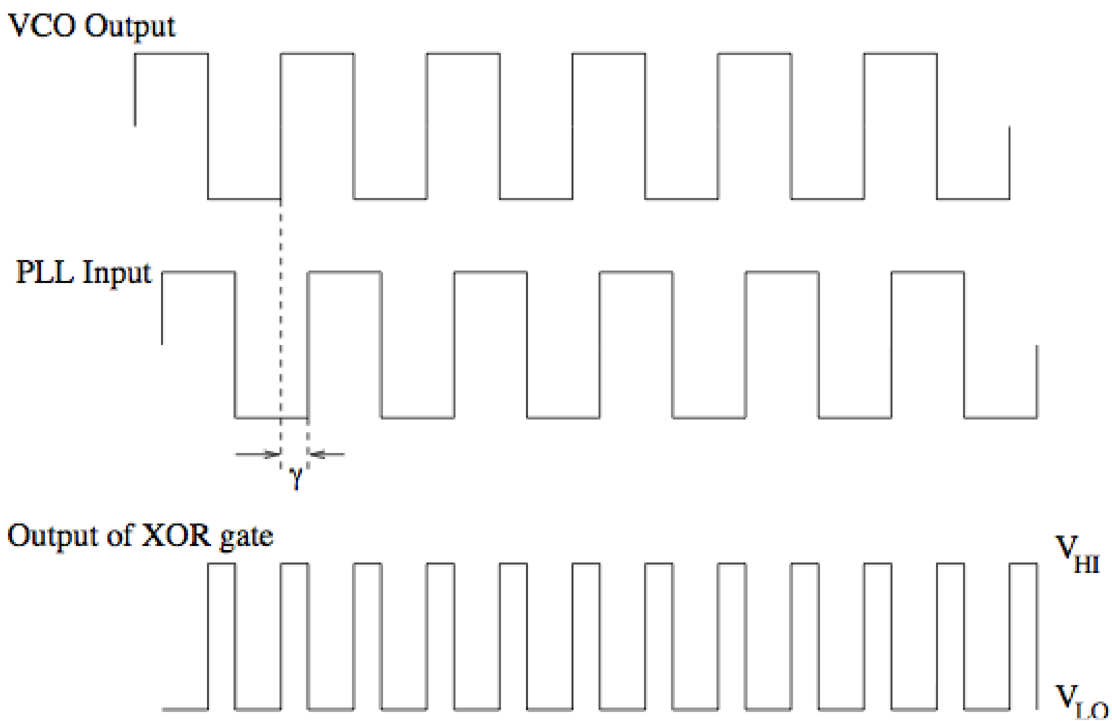
- Modern PLL implementation often make heavy use of digital logic
- For frequency synthesis application, VCO output is often a square wave (filtered later to extract sinusoid as a harmonic)
- Phase detector can also be implemented using digital logic, example, XOR gate

XOR-based phase detector



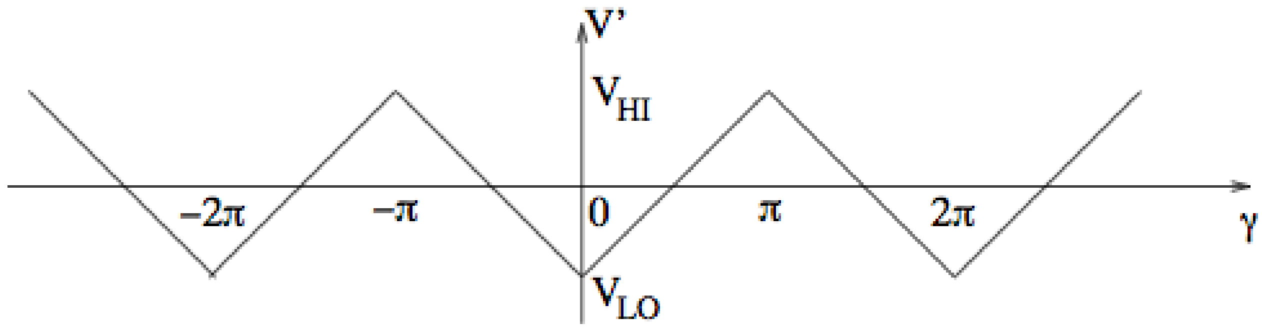


A	B	Output
0	0	0
0	1	1
1	0	1
1	1	0



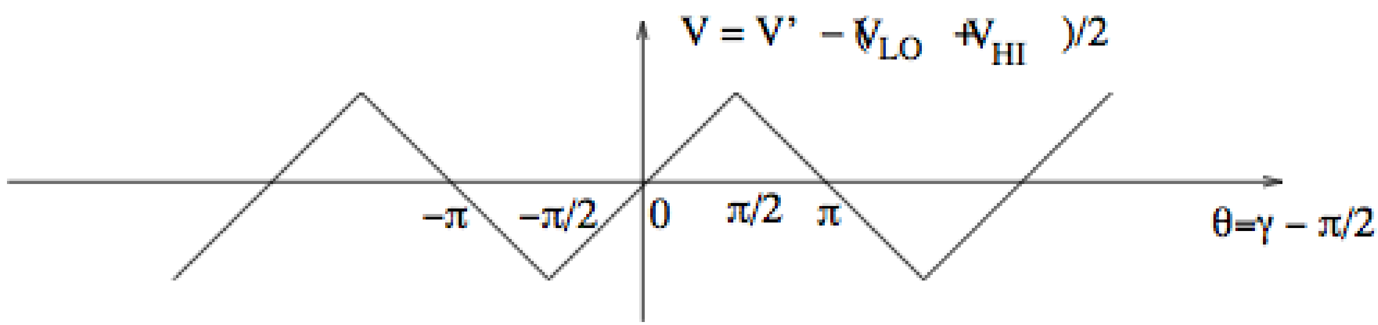
Average of XOR output is related to phase difference

XOR-based phase detector output



(a) DC value of output of XOR gate.

- Translate along both axes to get a more natural curve, i.e., phase detector output is zero for zero phase difference
- Response symmetric around origin



(b) XOR phase detector output after axes translation.

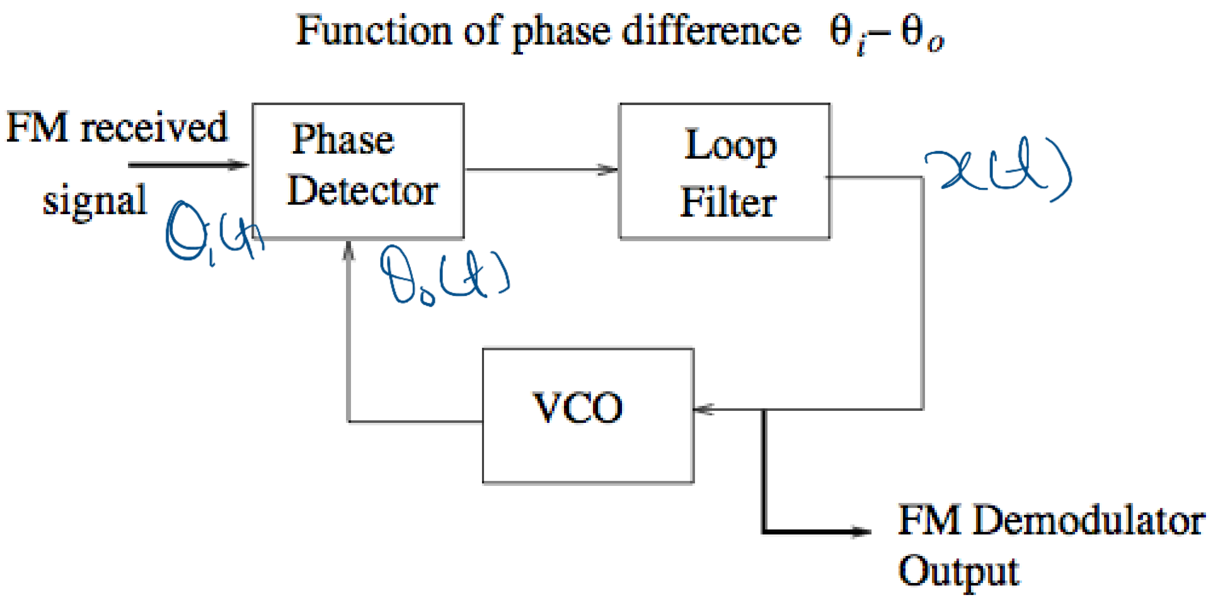
PLL Applications:

FM Demodulation

and

Frequency Synthesis

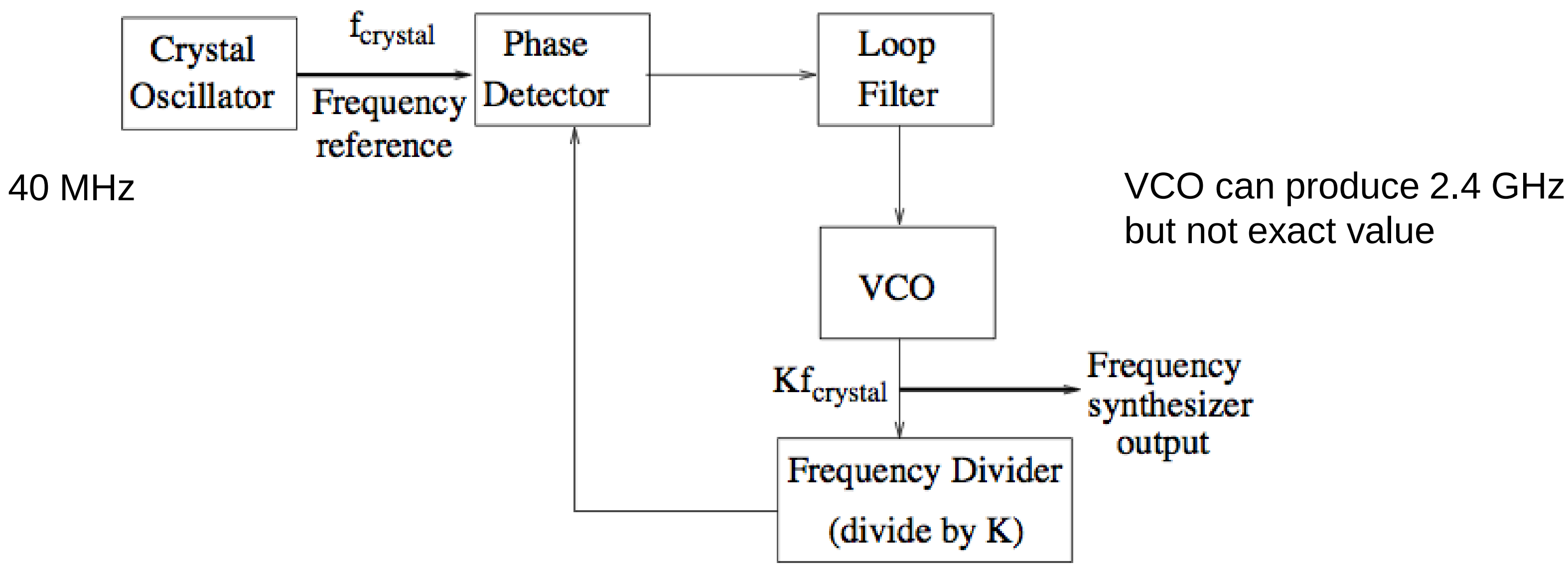
PLL for FM demodulation



- Show that if the PLL is tracking and PLL input is FM signal, then the input to VCO is a scaled version of the message.

PLL for frequency synthesis

- Typical application in communication transceivers
- Synthesize LO (e.g. at 2.4 GHz) from a lower reference frequency source (such as crystal oscillator)



- VCO quiescent frequency is around the desired frequency. Precise lock to multiple of crystal frequency is enabled by the PLL.
- Divide frequency of VCO (e.g., by skipping clock cycles in a digital implementation).
- Compare with crystal phase/freq to drive VCO