Chapter 4:
Broadcasting Communications and Frequency Division Multiplexing

AM/FM receivers, Spectrum Analyzer, FDMA, Television systems

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Lectured by
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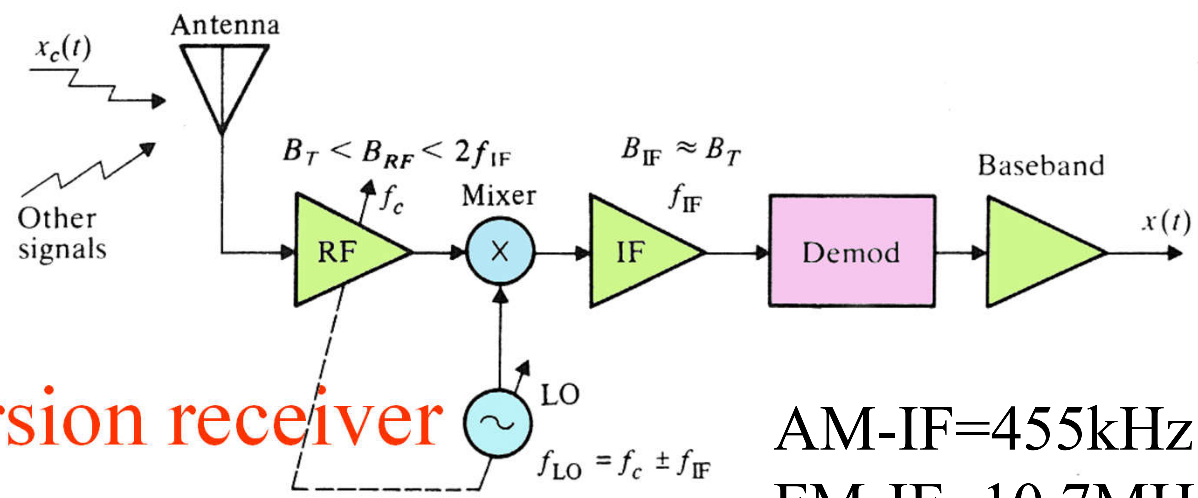
Slides with references from HUT Finland, Mc. Graw Hill Co., and A.B. Carlson's Communication Systems book

Broad Casting Systems

- Single conversion radio receiver,
  - AM radio (analog)
  - FM radio (analog) stereo multiplexing
- FM in Measurement equipment
  - Spectrum analyzer
- Multiplexing techniques in Telephone Systems
  - Frequency Division Multiplexing (FDM)
  - Quadrature-carrier multiplexing
- Phase-locked loop (PLL)
  - FM-demodulator
  - Frequency synthesis
  - Costas loop
- AM and FM in Television Systems



Heterodyne
Single-conversion receiver

AM-IF=455kHz
FM-IF=10.7MHz

- Assume reception of a bandpass signal

$$x_c(t) = A(t)\cos\left[\omega_c t + \phi(t)\right]$$

- Multiplication at the receiver with the local oscillator signal having frequency of f_{LO} yields signals at two CW-bands

$$\begin{aligned} x_{IF}(t) &= x_{LO}(t)x_c(t) \\ &= A(t)\cos(\omega_{LO}t)\cos\left[\omega_c t + \phi(t)\right] \\ &= A(t)\cos\left[(\omega_{LO} - \omega_c)t + \phi(t)\right]/2 + A(t)\cos\left[(\omega_{LO} + \omega_c)t + \phi(t)\right]/2 \end{aligned}$$

- Therefore, IF can be selected as $f_{IF} = f_{LO} \pm f_c$
or LO can be selected as $f_{LO} = f_c \pm f_{IF}$

Mirror frequency in radio systems

- Select for IF for instance $A_m(t)\cos\left[\left(\omega_{LO}-\omega_c\right)t+\phi(t)\right]/2$
- For the reason that cosine is even function there are two frequency bands that convert to intermediate frequency namely

$$\omega_{IF}=\left|\omega_{LO}-\omega_c\right|=\omega_{LO}-\omega_c \vee \omega_c{}'-\omega_{LO}$$

$$\Rightarrow \omega_c{}'=\omega_{LO}+\omega_{IF}\ ,\omega_c=\omega_{LO}-\omega_{IF}$$

  This means that both bandpass signals at the received frequencies $\omega_{LO}\pm\omega_{IF}$ are converted to the intermediate frequency.

- Example: Assume we set

$$f_{LO}=110\,\mathrm{MHz}, f_{IF}=10\,\mathrm{MHz}$$

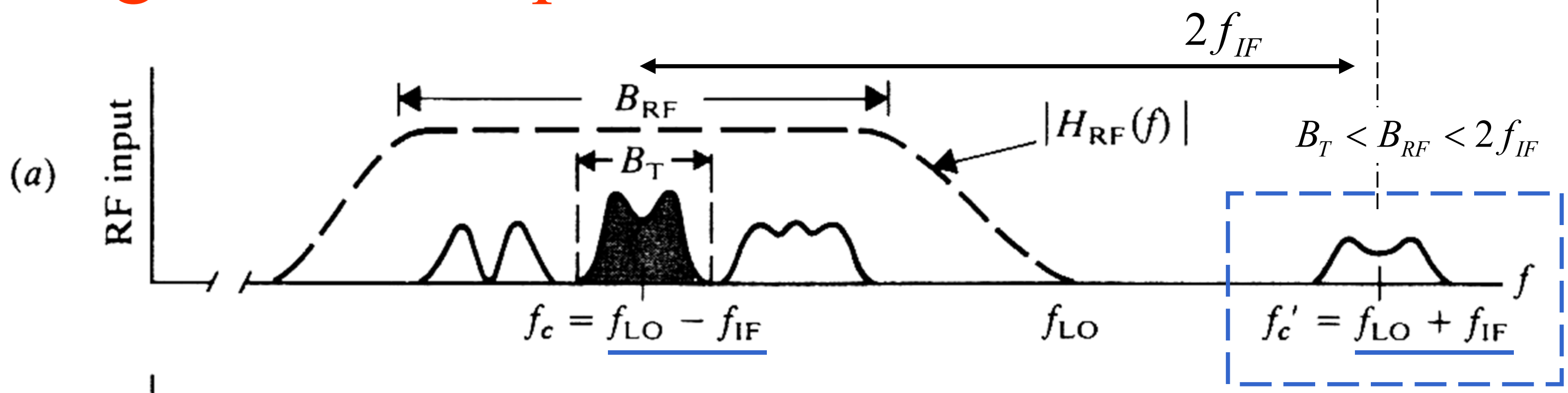
  therefore receiver picks signals at the bands of

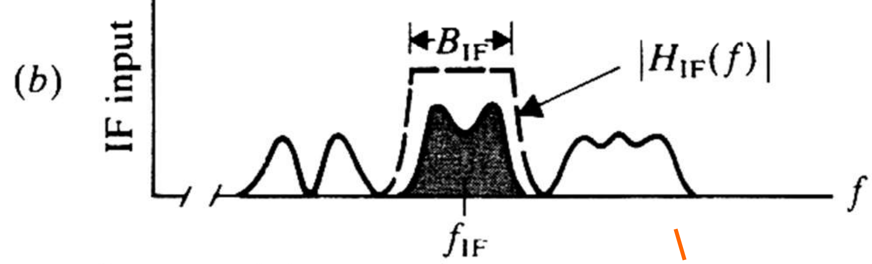
$$f_c=f_{LO}\pm f_{IF}=110\,\mathrm{MHz}\pm 10\,\mathrm{MHz}$$

$$=120\,\mathrm{MHz}\wedge 100\,\mathrm{MHz}$$

- However, this is usually not wanted, and the other band must be filtered away by the first bandpass filter at the receiver

Filtering mirror frequencies (image rejection filtering)

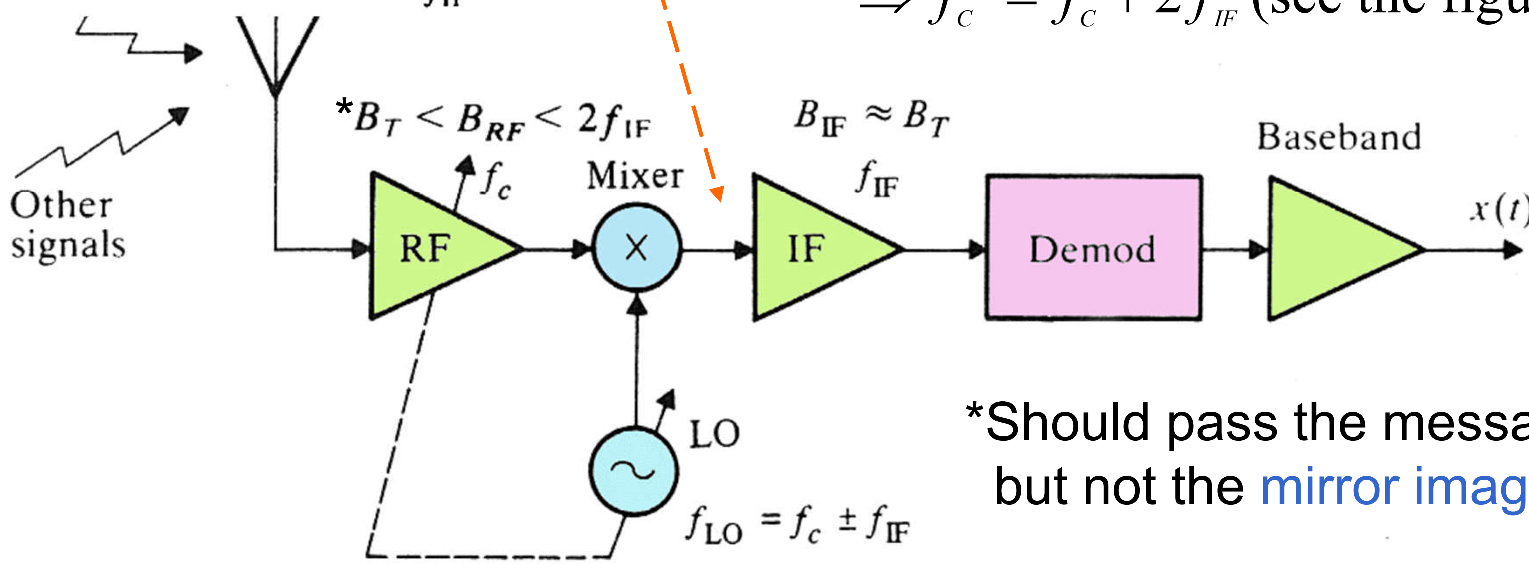




$$f_{IF} = f_{LO} \pm f_C$$

$$f_C = f_{LO} - f_{IF} \text{ (selected)}$$

$$\Rightarrow f_C' = f_C + 2f_{IF} \text{ (see the figure)}$$



*Should pass the message but not the mirror image

Single conversion - basic characteristics

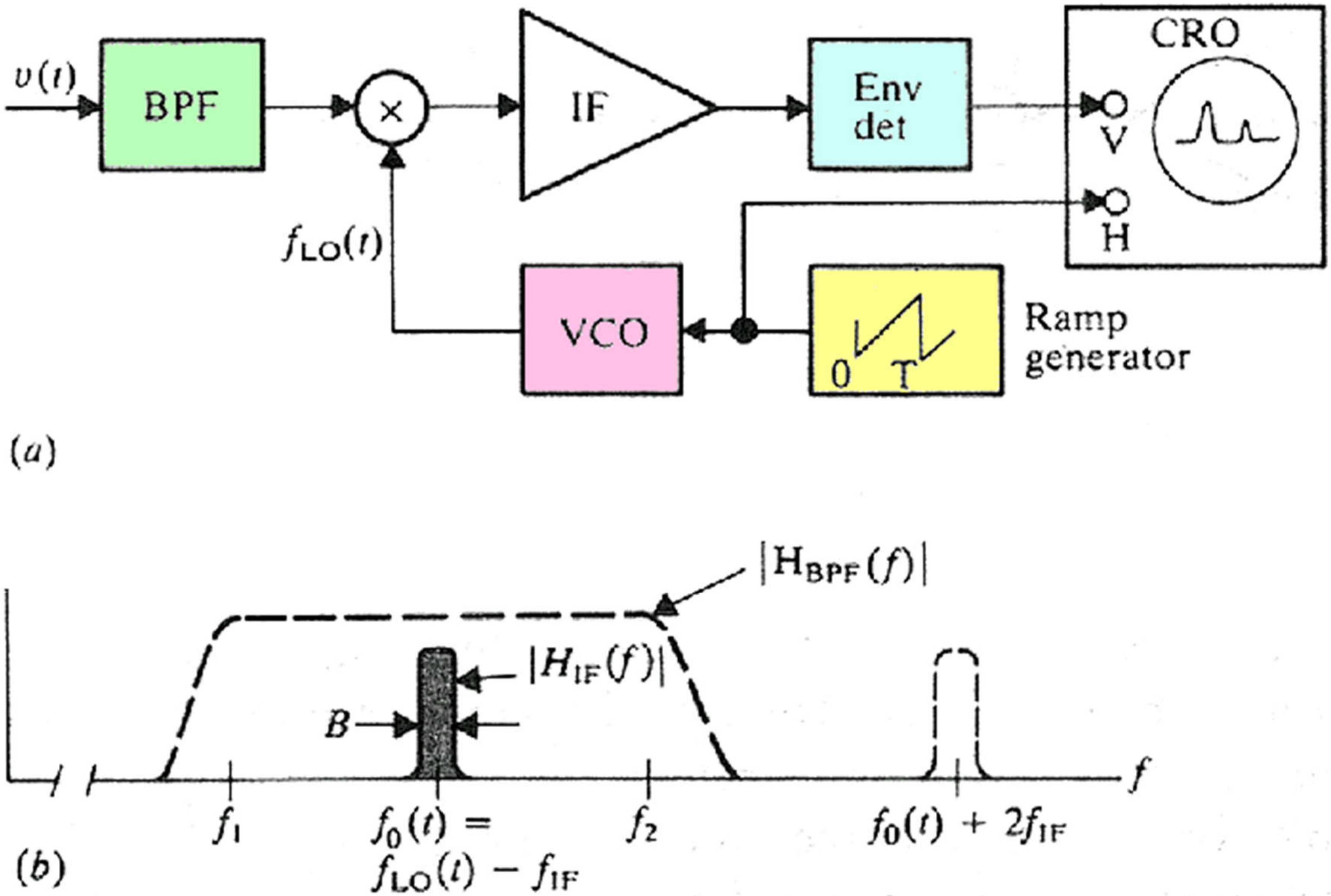
- Single conversion can be used with all CW methods
- The RF stage provides image rejection
- The IF stage provides gain and interference rejection
  - note that the fractional BW= B_T/f_{IF} is selected by adjusting f_{IF}
- Remember from the second lecture that system design is easier if the fractional bandwidth is kept relatively small: For analog FM broadcasting:

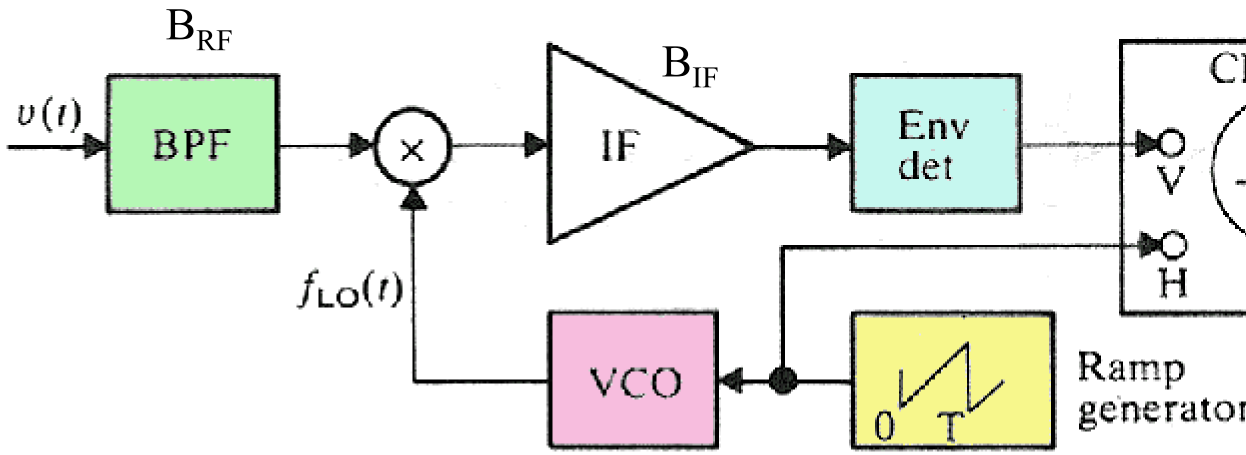
$$B_{IF}/f_{IF} = 200\text{kHz}/10.7\text{MHz} = 0.02$$

when it was required $0.01 < B / f_0 < 0.1$

- Tuning of the receiver to a desired band is easy by adjusting the local oscillator. (Often B_{RF} is selected to be so wide and f_{LO} so high that the first bandpass filter (amplifier) center frequency requires no tuning, as usually in FM radios)

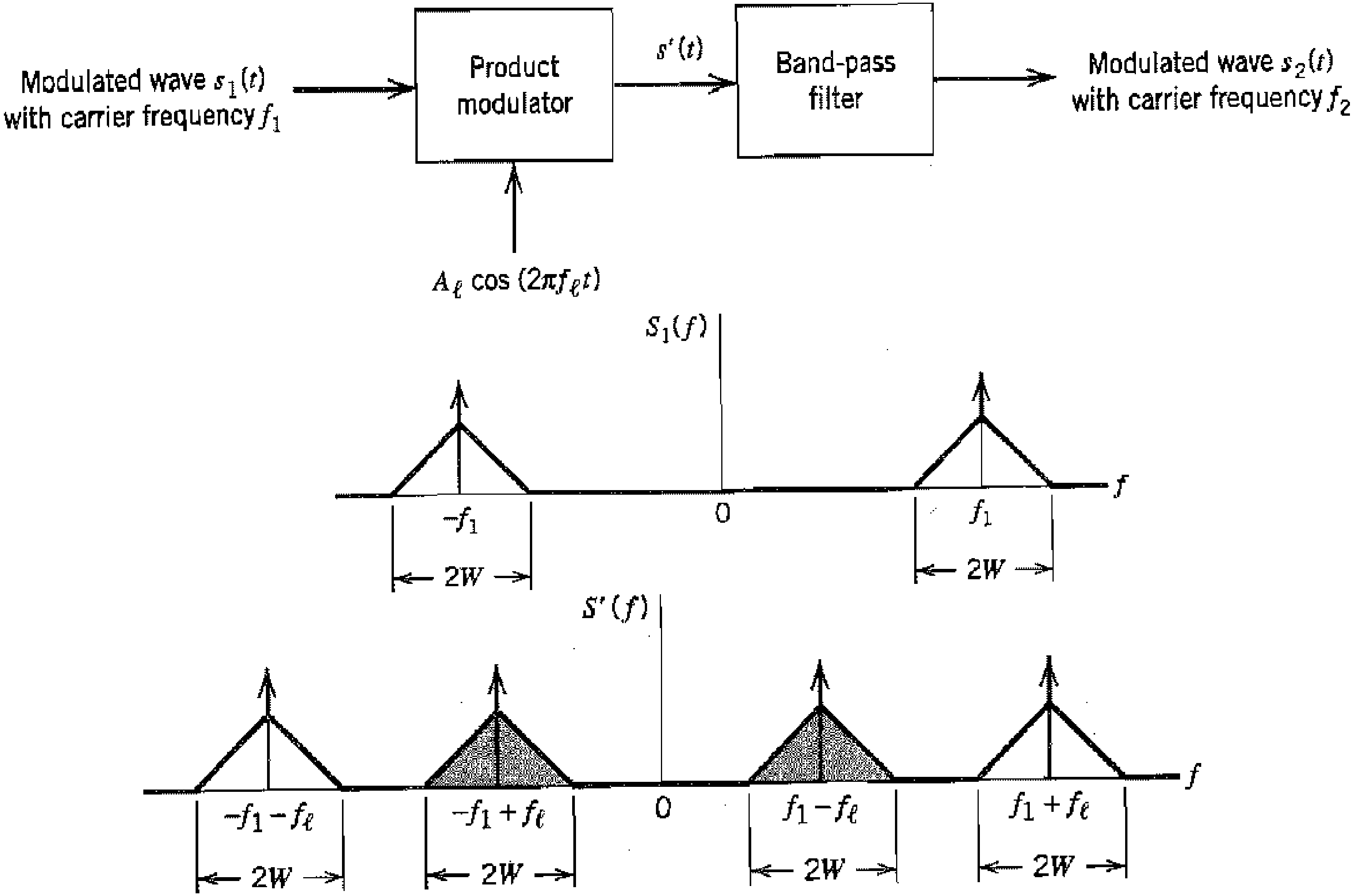
Frequency Modulation in Scanning spectrum analyzer



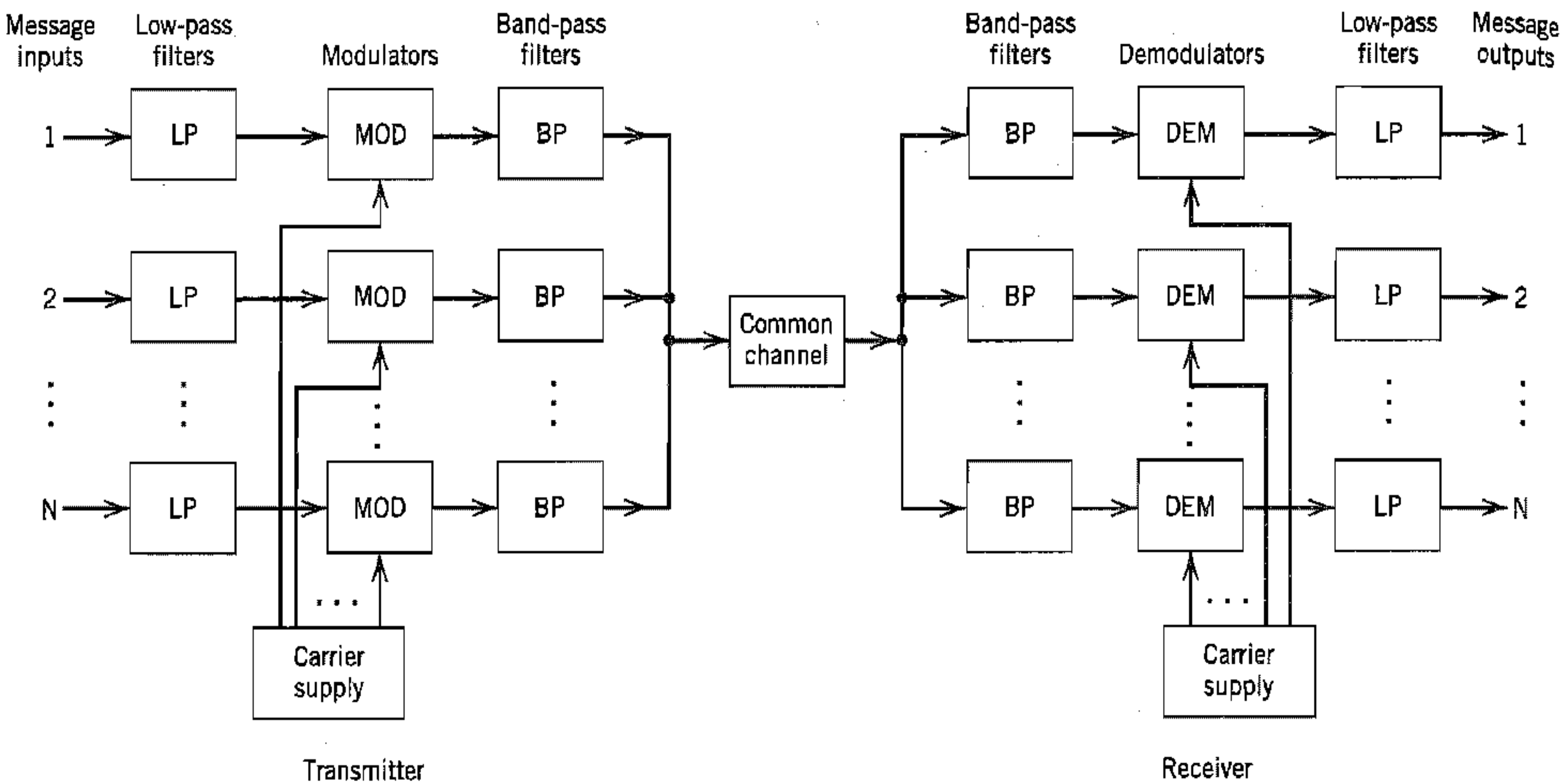


- VCO, B_{RF} and B_{IF} filters form together a scanning bandpass filter (SBF)
- Ramp generator takes care of sweeping SBF
- After the IF filter the envelope detector yields signal whose power is comparable to the power that has passed the SBF
- Sweep rate and B_{IF} determine system resolution. High resolution->small B_{IF} and sweep rate as discussed soon
- When larger sensitivity is desired sweep rate must be decreased
- Spectrum analyzer includes often integrator (or averaging function) to improve SNR via inclusion of multiple sweep data

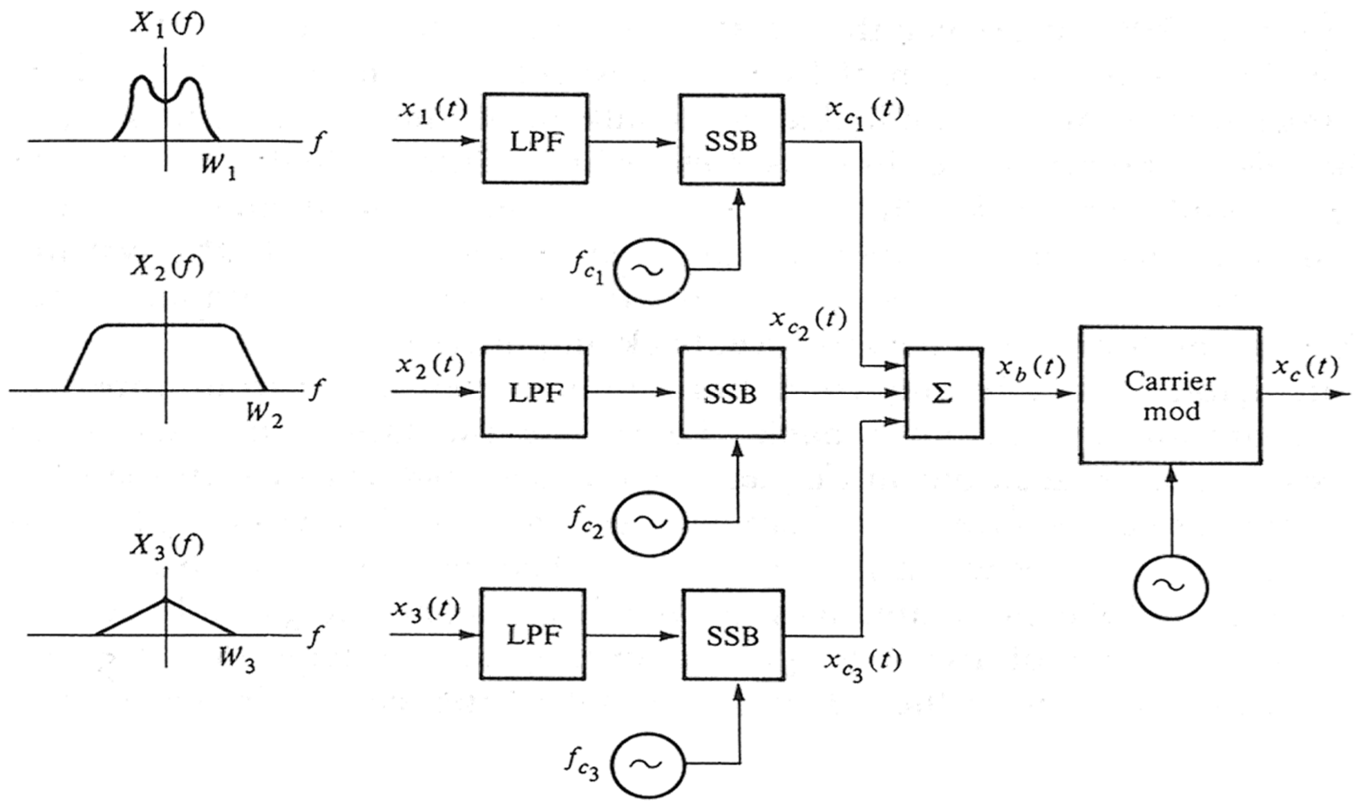
FREQUENCY TRANSLATION - Mixer



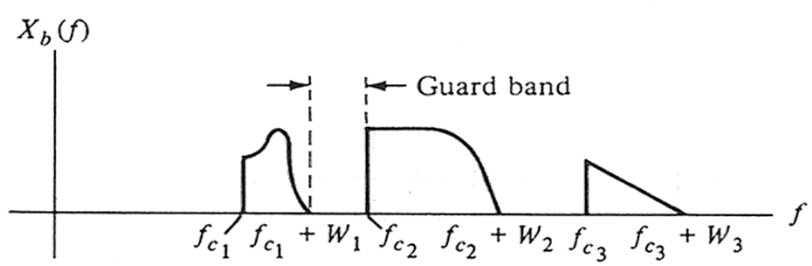
FREQUENCY DIVISION MULTIPLEXING (FDM)



Frequency-Division Multiplexing (FDM)



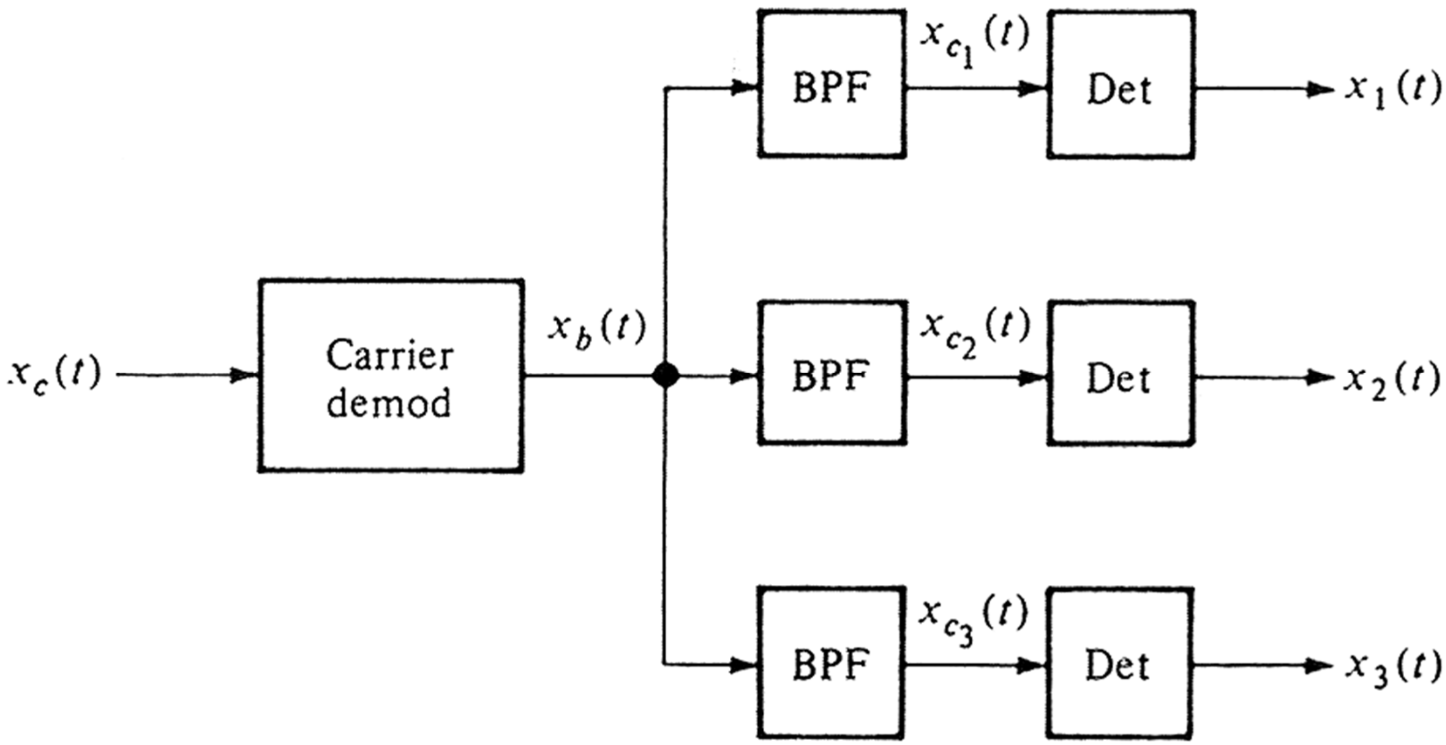
(a)



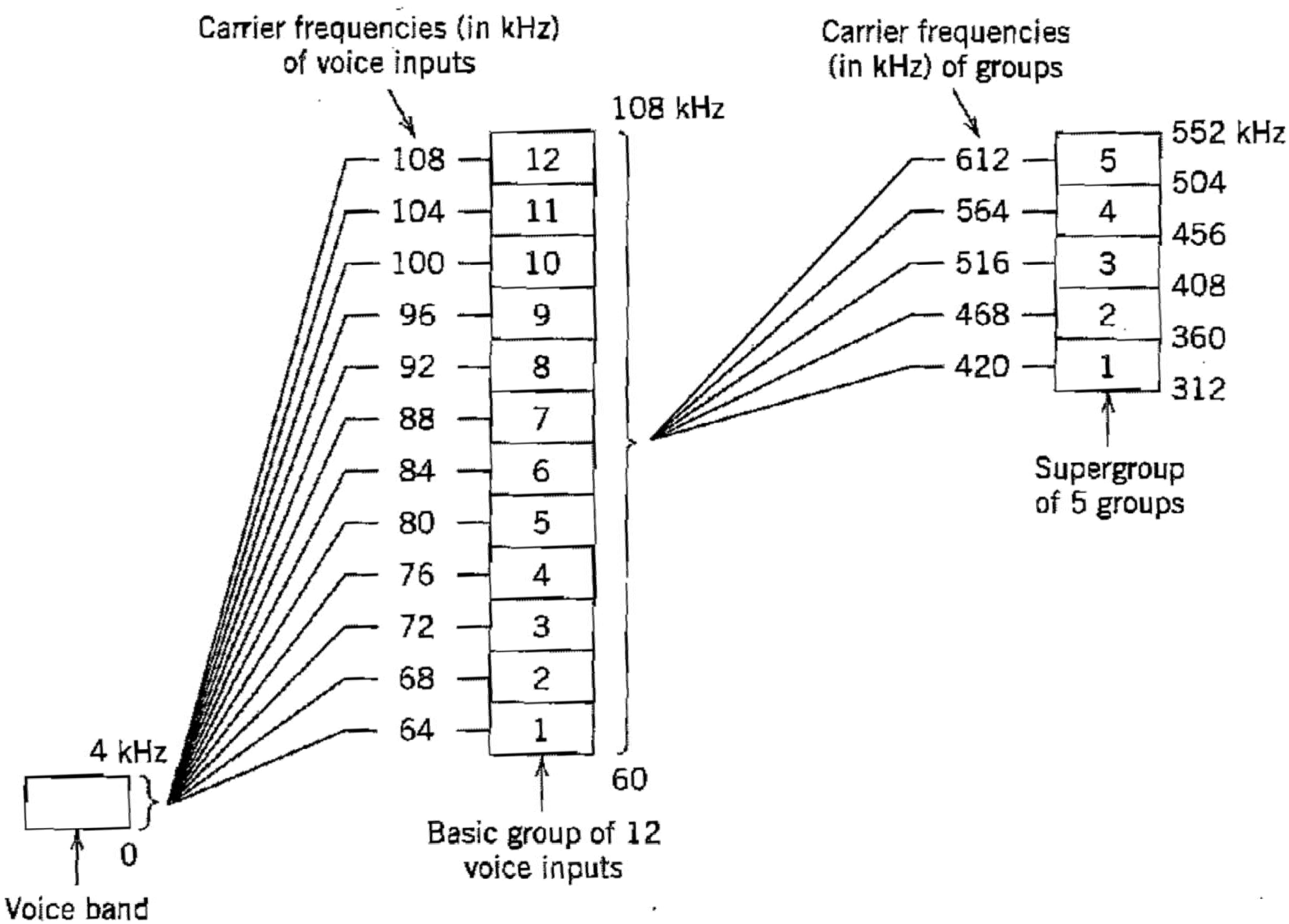
(b)

FDM receiver

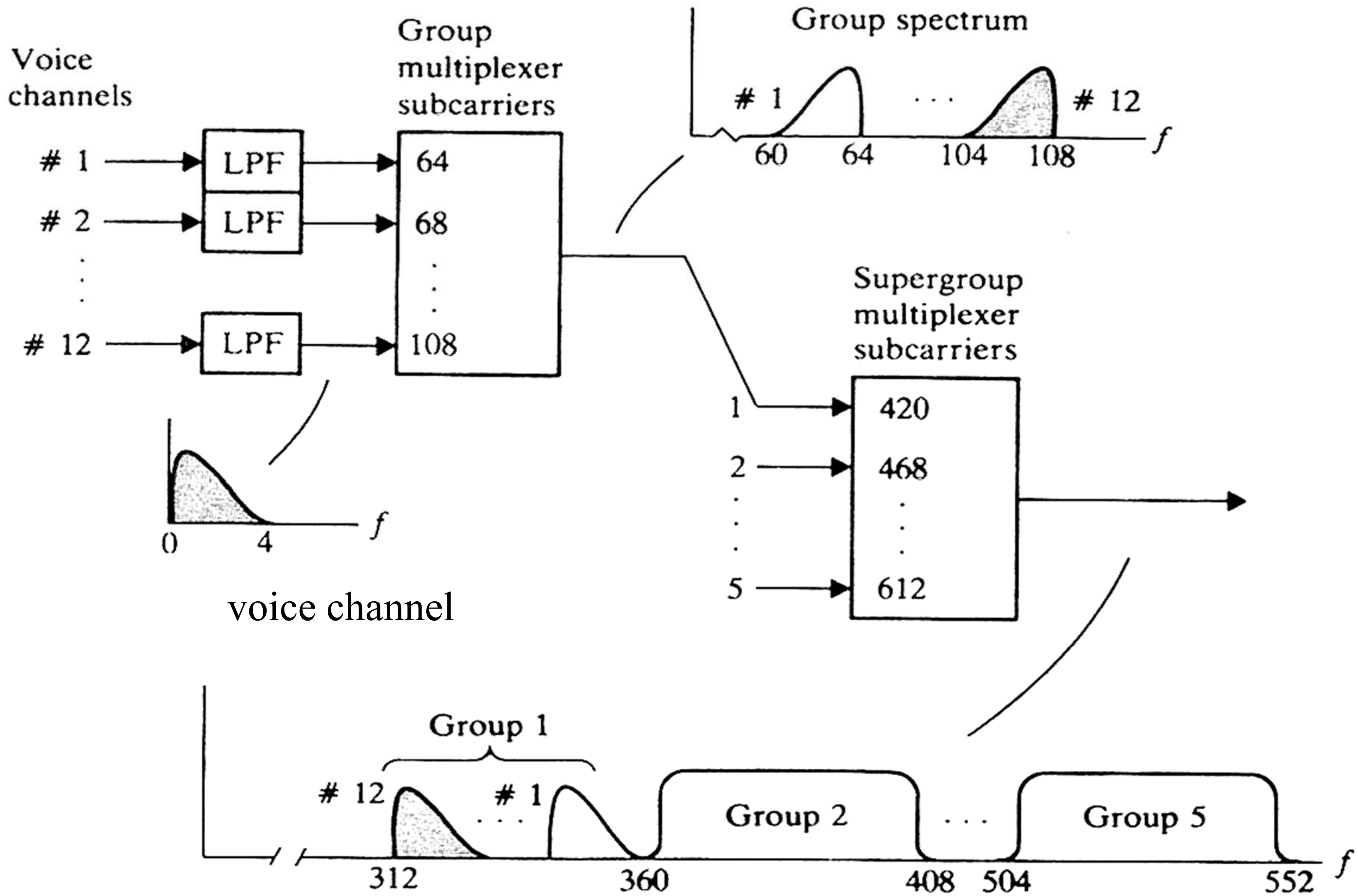
First the FDM wave is demodulated. Then each subcarrier is detected by using separate bandpass filters and detectors.



Example of FDM in Telephone Systems



AT & T standard FDM-hierarchy in PSTN

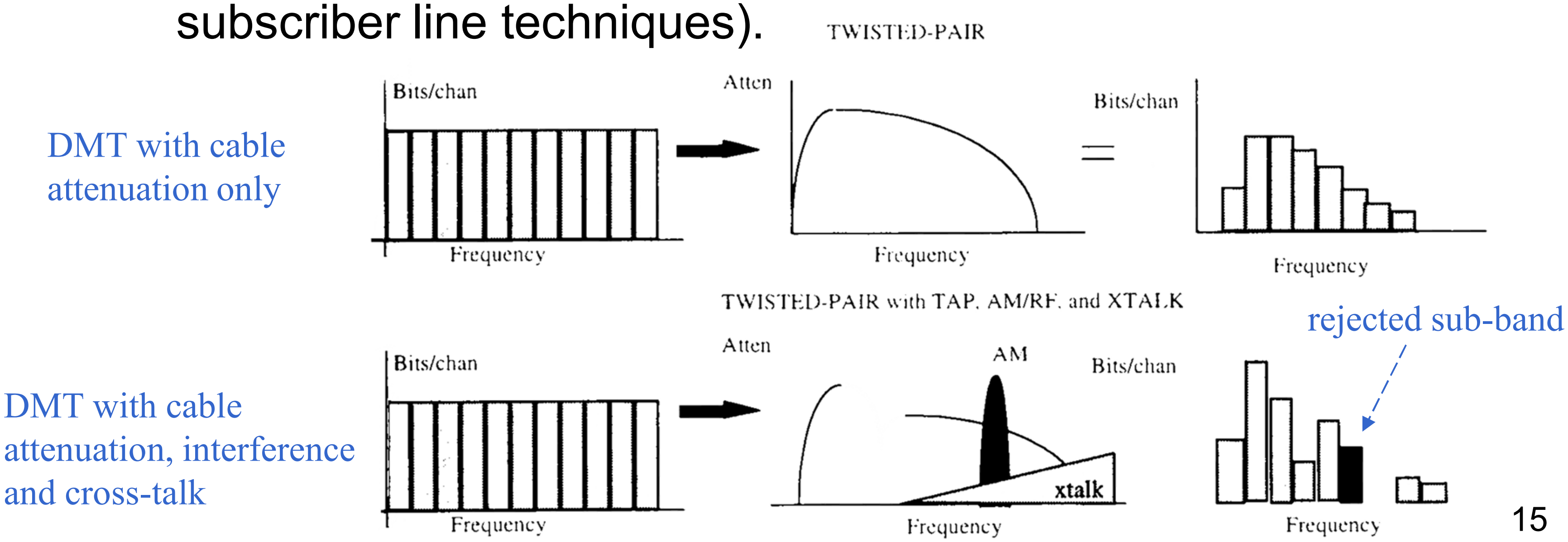


voice channel

Supergroup spectrum

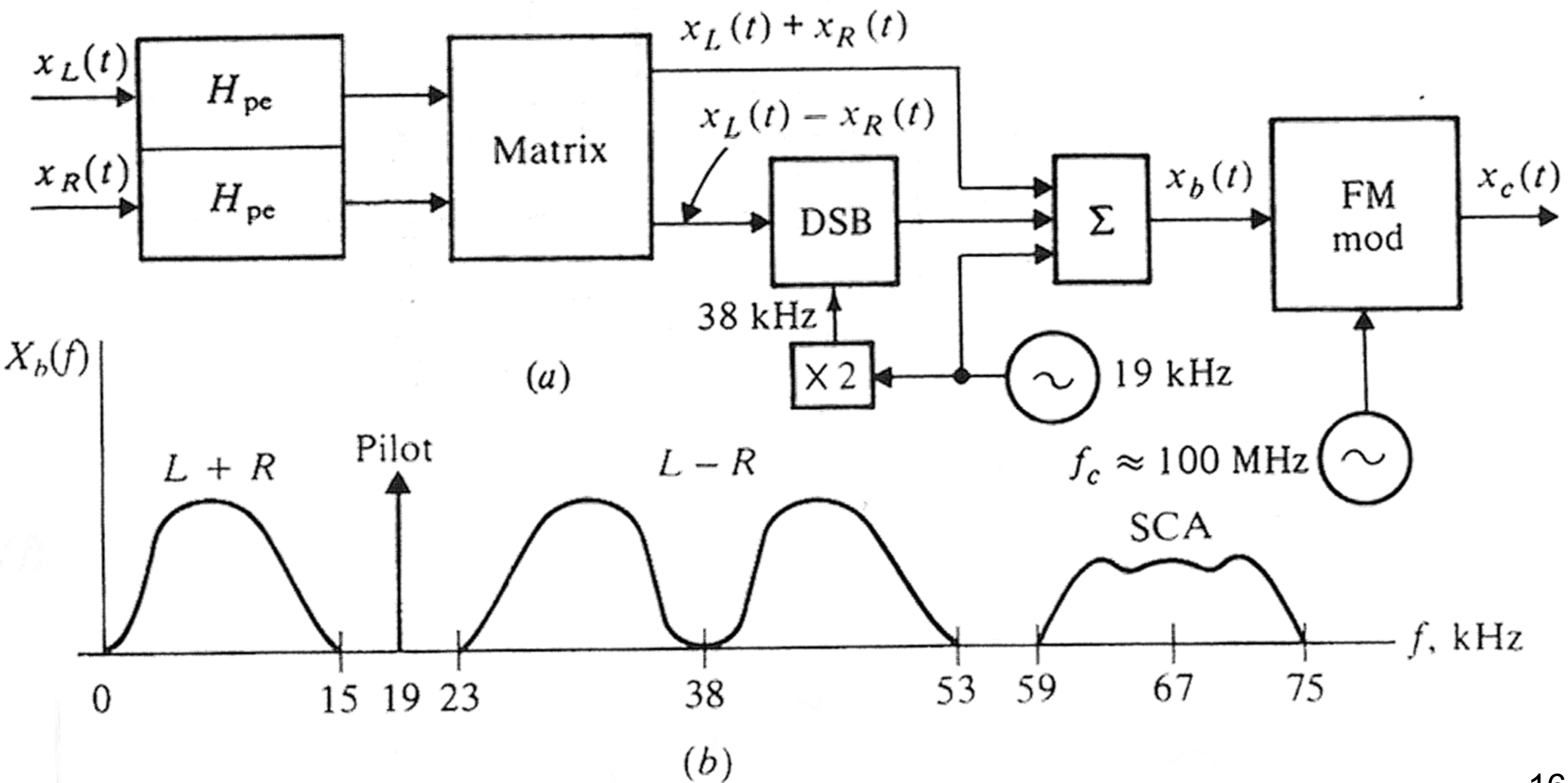
Advanced FDM: xDSL with OFDM

- Conventional FDM:
  - Each channel occupies accurately certain frequency band
  - Bandwidth efficiency increased by using SSB modulation
  - Usage of guard bands wastes resources
  - A lot of filtering functions (complex circuitry)
- Modern FDM: OFDM (orthogonal frequency division multiplexing) and DMT (discrete multitone modulation) yield increased spectral adaptation. Applied in xDSL (digital subscriber line techniques).



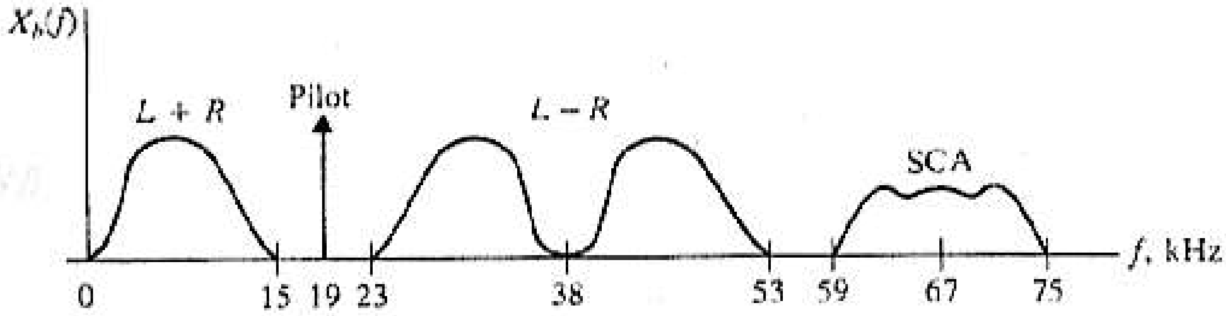
FM stereo multiplexing (MPX-system)

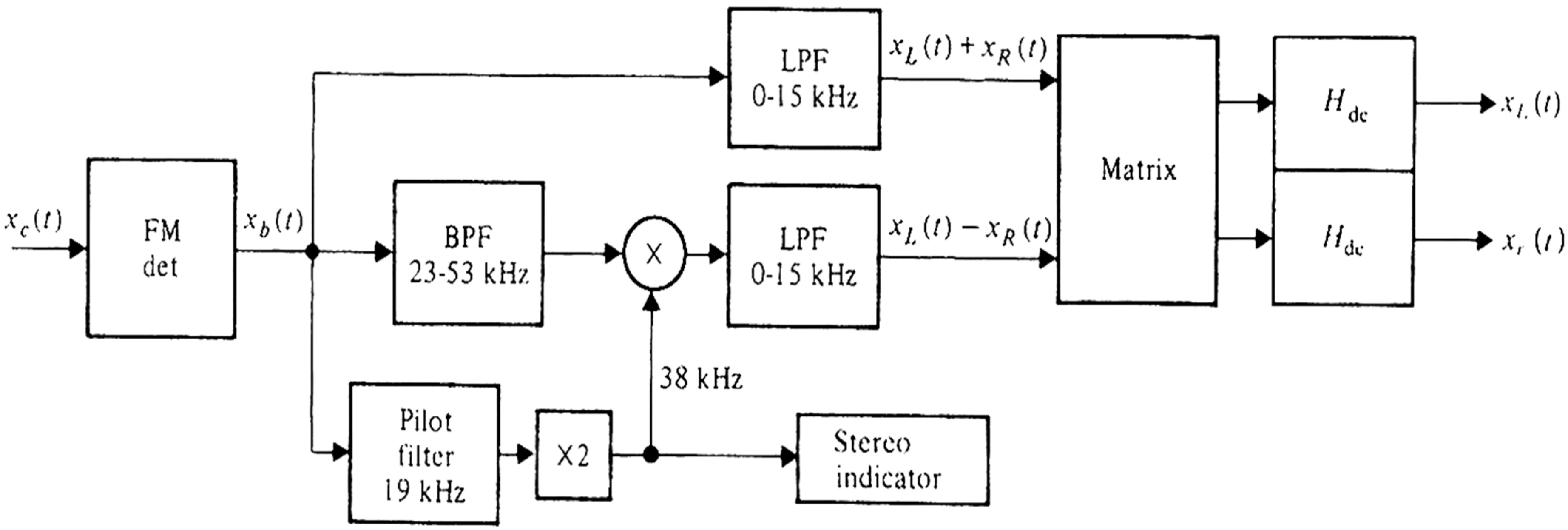
- The MPX encoder utilizes various linear modulation methods
- L+R and L-R signals are transmitted on different channels
- SCA (Subsidiary Communication Authorization) is used to transmit background music for selected subscribers



FM stereo decoder

- Compatibility to mono-phonic transmission is granted by using the unmodulated L+R and DSB modulated L-R signal at 23-53 kHz that is automatically filtered out in mono-phonic reception



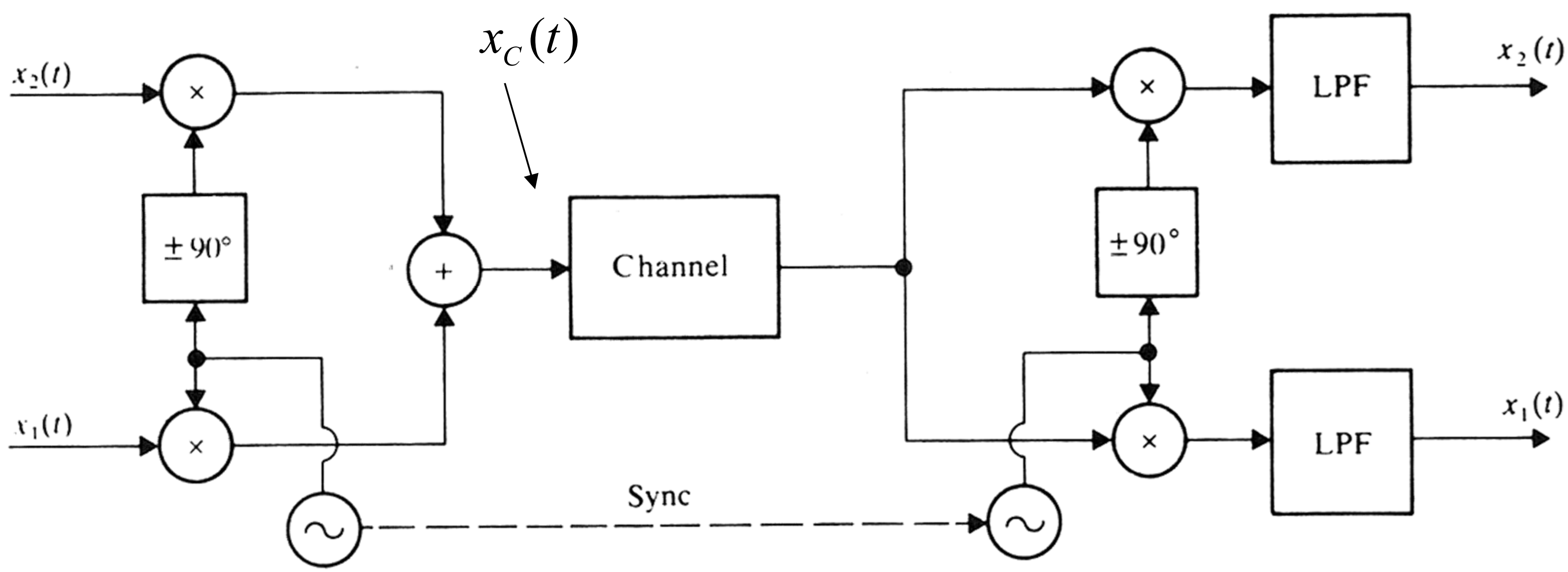


Class of Service	Item	FCC Standard
FM broadcasting	Assigned frequency, f_c	In 200-kHz increments from 88.1 MHz (FM Channel 201) to 107.9 MHz (FM Channel 300)
	Channel bandwidth	200 kHz
	Noncommercial stations	88.1 MHz (Channel 201) to 91.9 MHz (Channel 220)
	Commercial stations	92.1 MHz (Channel 221) to 107.9 MHz (Channel 300)
	Carrier frequency stability	±2,000 Hz of the assigned frequency
	100% modulation[a]	$\Delta F = 75$ kHz
	Audio frequency response[b]	50 Hz to 15 kHz, following a 75-μs preemphasis curve
	Modulation index	5 (for $\Delta F = 75$ kHz and $B = 15$ kHz)
	% harmonic distortion[b]	<3.5% (50–100 Hz) <2.5% (100–7500 Hz) <3.0% (7500–15,000 Hz)
	FM noise	At least 60 dB below 100% modulation at 400 Hz
	AM noise	50 dB below the level corresponding to 100% AM in a band 50 Hz–15 kHz
	Maximum power licensed	100 kW in horizontal polarized plane plus 100 kW in vertical polarized plane

Class of Service	Item	FCC Standard
Two-way FM mobile radio	100% modulation	$\Delta F = 5\text{kHz}$
	Modulation index	1 (for $\Delta F = 5$ kHz and $B = 5$ kHz)
	Carrier frequencies are within the frequency bands	32–50 MHz (low VHF band) 144–148 MHz (2-m amateur band) 148–174 MHz (high VHF band)[c] 420–450 MHz ($\frac{3}{4}$-m amateur band) 450–470 MHz (UHF band) 470–512 MHz (UHF, T band) 806–928 MHz (900-MHz band)
Analog TV aural (FM) signal	100% modulation	$\Delta F = 25$ kHz
	Modulation index	1.67 (for $\Delta F = 25$ kHz and $B = 15$ kHz)

Quadrature-carrier multiplexing

- Two signals x_1 and x_2 are transmitted via same channel
  $$x_c(t) = A_c\left[x_1(t)\cos(\omega_c t) \pm x_2(t)\sin(\omega_c t)\right]$$
- Signals can be analog or digital CW or baseband signals (QPSK, DSB, SSB ...)



Task: show that the signals x_1 and x_2 can be detected ***independently*** *at the receiver!*

Quadrature-carrier reception

- In order to detect the x_1 component multiply by the cosine-wave:

$$\cos(\omega_c t)\left[x_1(t)\cos(\omega_c t) \pm x_2(t)\sin(\omega_c t)\right]$$
$$= x_1(t)\left[1-\cos(2\omega_c t)\right]/2 \pm x_2(t)\sin(2\omega_c t)/2$$

- In order to detect the x_2 component multiply by sine-wave:

$$\sin(\omega_c t)\left[x_1(t)\cos(\omega_c t) \pm x_2(t)\sin(\omega_c t)\right]$$
$$= x_2(t)\left[1-\cos(2\omega_c t)\right]/2 \pm x_1(t)\sin(2\omega_c t)/2$$

- Note
  - Second-order frequency must be filtered away
  - The local oscillator must be precisely in-phase to the received signal, otherwise cross-talk will follows

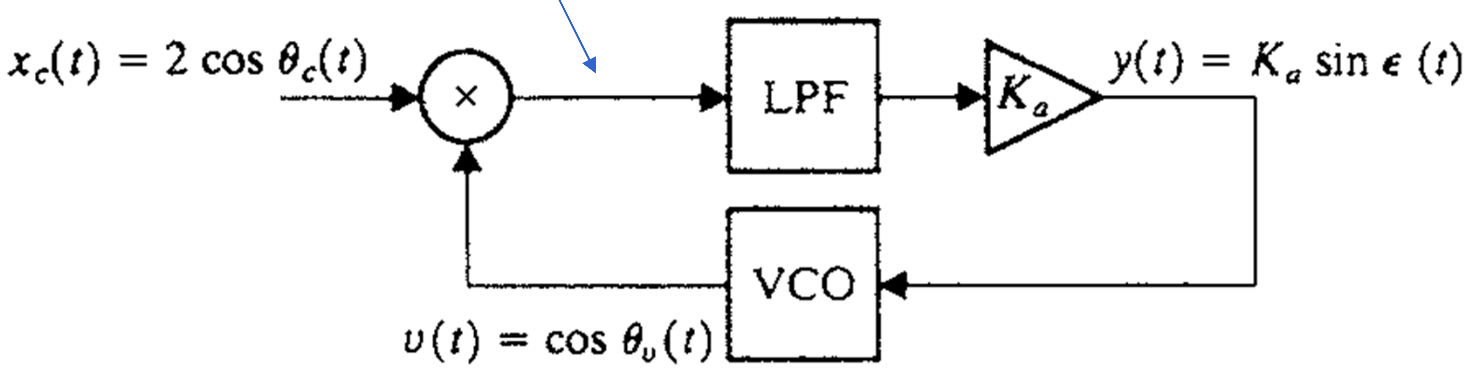
Phase-locked loops (PLLs)

- Phase-locked loop is a feedback arrangement capable to synchronize itself to a noisy external reference
- The output signals of the loop can be used to produce for instance multitude of locked frequencies
- PLL application areas include...
  - modulators
  - demodulators
  - frequency synthesis
  - multiplexers
  - signal processors

The PLL principle

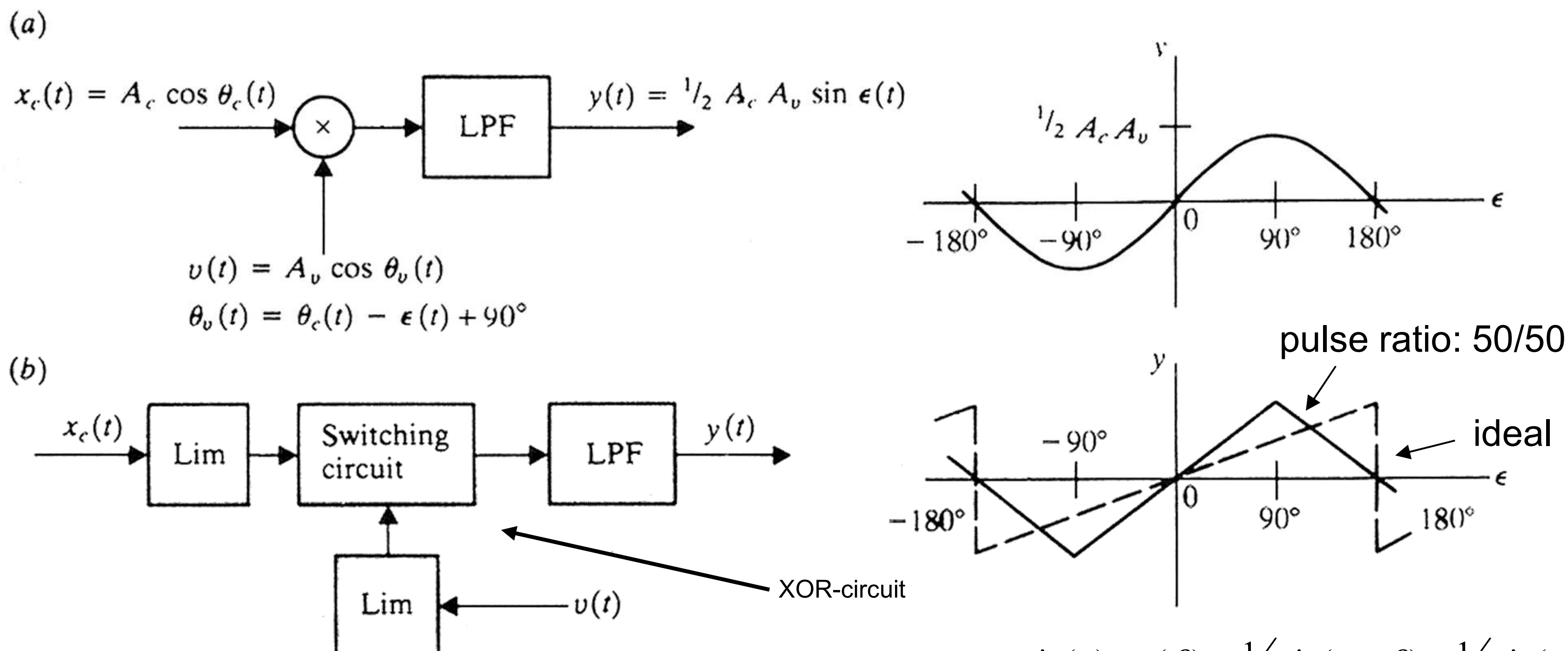
- The PLL circuit consists of
  – phase comparator (in the figure below the multiplier)
  – lowpass filter
  – feedback amplifier
  – VCO (voltage controlled oscillator), whose **output frequency is linearly proportional to input amplitude**
- Principle: phase difference of $X_c(t)$ and $v(t)$ adjusts VCO

Phase comparator output is
comparable to phase difference of input signals



PLL phase comparator realizations

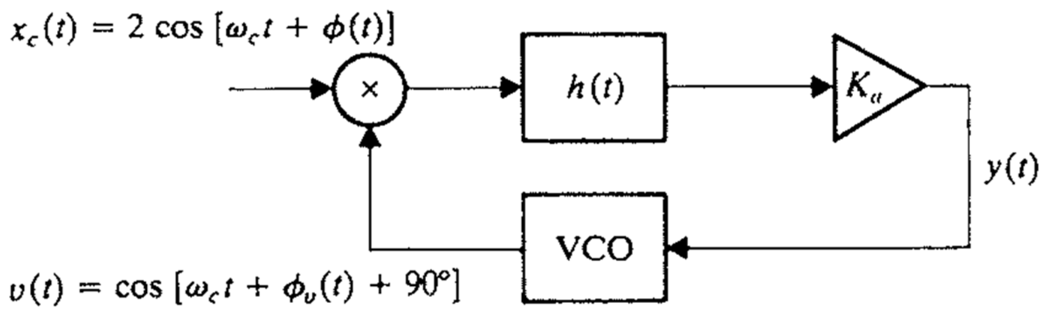
- Circuits: (a) analog and (b) digital phase comparator circuit
- Note that for (a) output is proportional to
  - input signal phase difference
  - input signal amplitudes (unintended AM thus harmful)
- In (b) AM effects are compensated and response is more linear



$$\sin(a)\cos(\beta) = \frac{1}{2}\sin(\alpha - \beta) + \frac{1}{2}\sin(\alpha + \beta)$$

FM detection by PLL

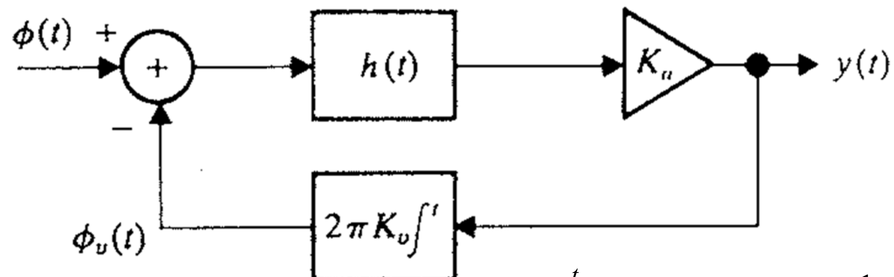
(a)



time domain

(b)

$$\sin\varepsilon(t) \approx \varepsilon(t) = \phi(t) - \phi_v(t)$$

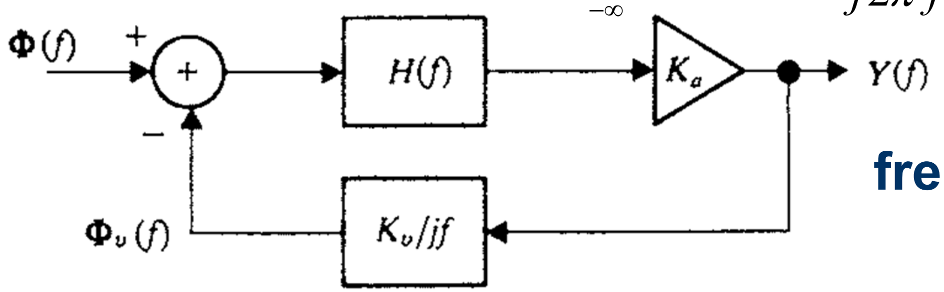


$$\phi_v(t) = 2\pi K_v \int_t y(t)dt$$

phase domain

$$\int_{-\infty}^{t} v(\lambda)d\lambda \Leftrightarrow \frac{1}{j2\pi f}V(f) + \frac{1}{2}V(0)\delta(f)$$

(c)

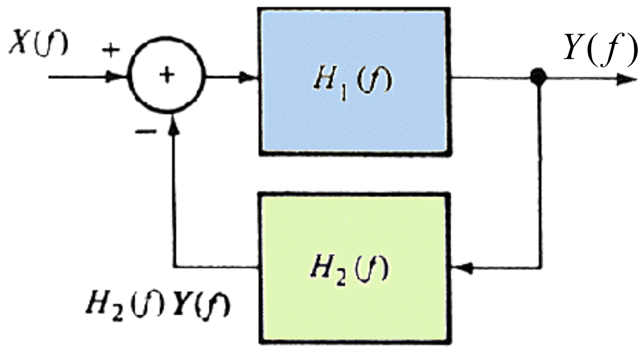


$$\begin{cases} \omega(t) = \dfrac{d\phi_v(t)}{dt} \\ \phi_v(t) = \int_{-\infty}^{t} \omega(\alpha)d\alpha \end{cases}$$

frequency domain

PLL FM-demodulator: the feedback analysis

Solve transfer function with feedback:

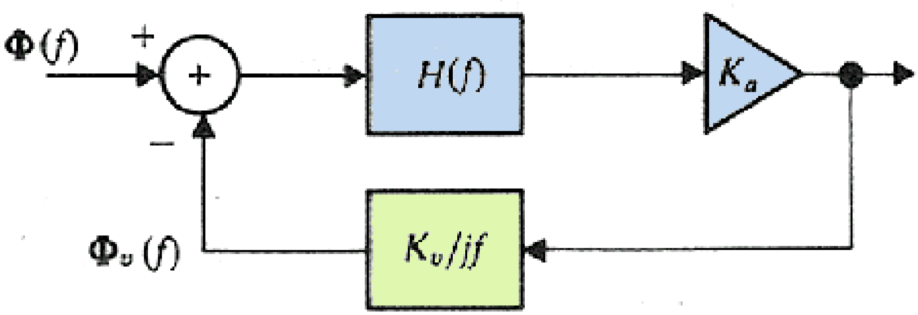


$$Y(f) = \left(X(f) - H_2(f)Y(f)\right)H_1(f)$$

$$Y(f) + H_1(f)H_2(f)Y(f) = X(f)H_1(f)$$

$$Y(f) = \frac{H_1(f)}{1 + H_1(f)H_2(f)}X(f)$$

This is applied to the **linearized PLL** yielding relationship between the input phase and output voltage:



$$Y(f) = \frac{K_a H(f)}{1 + K_a H(f) K_v / jf}\Phi(f)$$

$$= \frac{1}{K_v}\frac{jfKH(f)}{jf + KH(f)}\Phi(f)$$

$$(K = K_a K_v)$$

Applying the FM signal to the linearized PLL model

- Remember the FM wave:

$$d\phi(t)/dt = 2\pi f_{\Delta} x(t)$$

where the modulating signal is denoted by *x(t).* The input FM phase to the system is thus

$$\phi(t) = 2\pi f_{\Delta} \int_t x(\lambda) d\lambda$$

- This is in frequency domain: $\Phi(f) = 2\pi f_{\Delta} X(f)/(j2\pi f)$

assuming no DC component or $V(0) = 0$, or

$$\int_t v(\lambda) d\lambda \Leftrightarrow \frac{1}{j2\pi f} V(f) + \underbrace{\tfrac{1}{2} V(0)\delta(f)}_{=0}$$

Applying FM signal to the detector... (cont.)

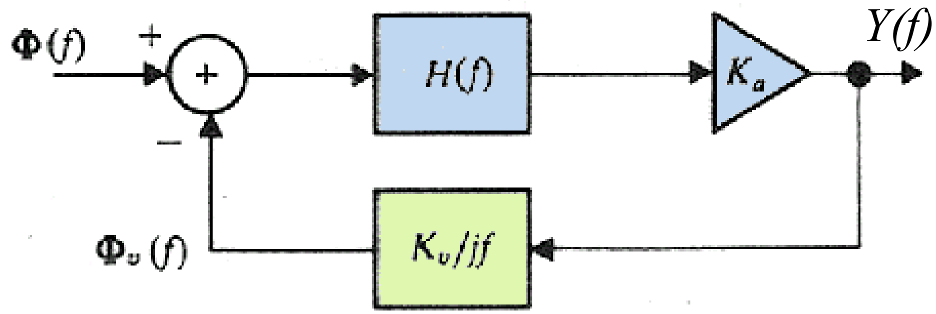
- Thus the input is $\Phi(f) = f_\Delta X(f)/(jf)$ and the output is

$$Y(f) = \frac{1}{K_v}\frac{jfKH(f)}{jf + KH(f)}\Phi(f) = \frac{f_\Delta X(f)}{K_v}H_L(f)$$

where the loop equivalent transfer function is

$$H_L(f) = \frac{H(f)}{H(f) + j(f/K}$$

$$K = K_a K_v$$



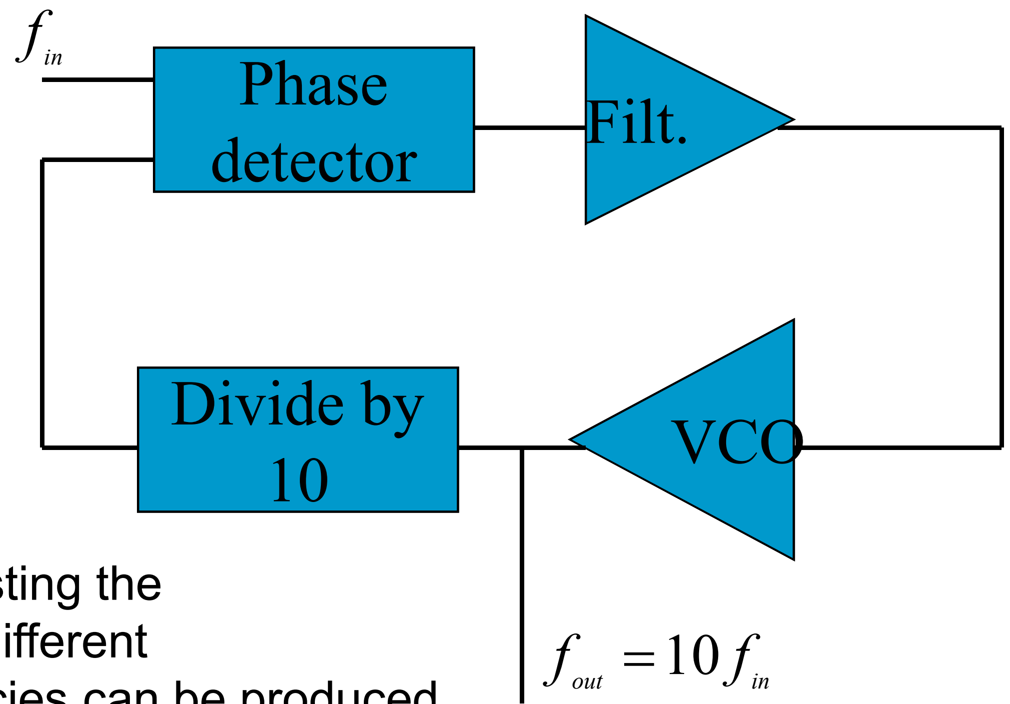
- Assume that the first order LP function is used or

$$H_L(f) = \frac{1}{1 + j(f/K)} \Rightarrow Y(f) \approx \frac{f_\Delta}{K_v}\frac{X(f)}{1 + j(f/K)} \approx \frac{f_\Delta}{K_v}X(f), \frac{W}{K} << 1$$

$$\Rightarrow y(t) \approx \frac{f_\Delta}{K_v}x(t)$$

PLL based frequency synthesizer

Reference signal f_{in}
is locked for instance
to the fundamental frequency
of a crystal oscillator



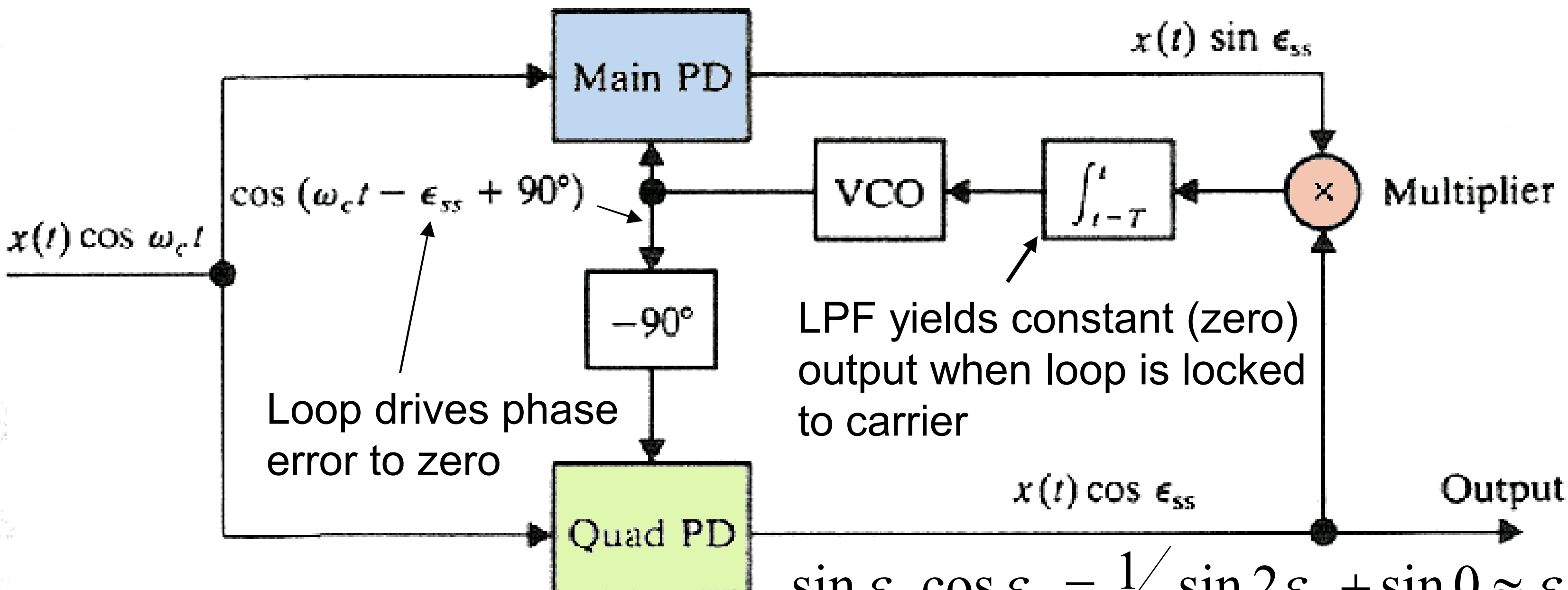
By adjusting the
divider different
frequencies can be produced
whose phase is locked into f_{in}

Detecting DSB using PLL-principle

- An important application for PLLs is in **synchronization** of receiver local oscillator in synchronous detection
- In the **Costas PLL** (below) two phase discriminators are used to:
  - cancel out DSB modulation *x(t)* in the driving signal
  - synchronize the output frequency to the center frequency of the DSB spectra (the suppressed carrier)
  - to detect the DSB signal

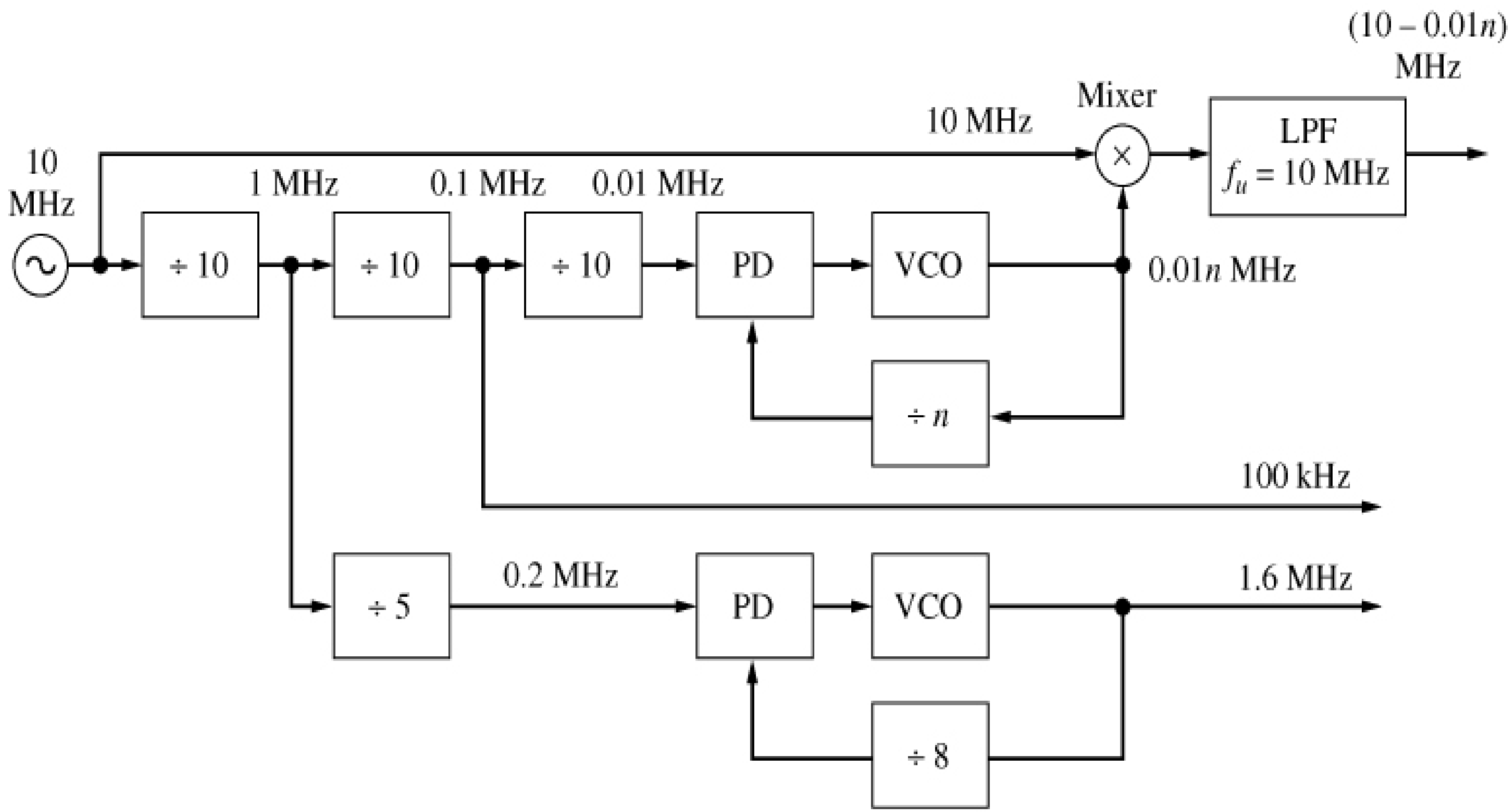
PD: phase detector (=multiply+LPF)

Costas PLL detector for DSB

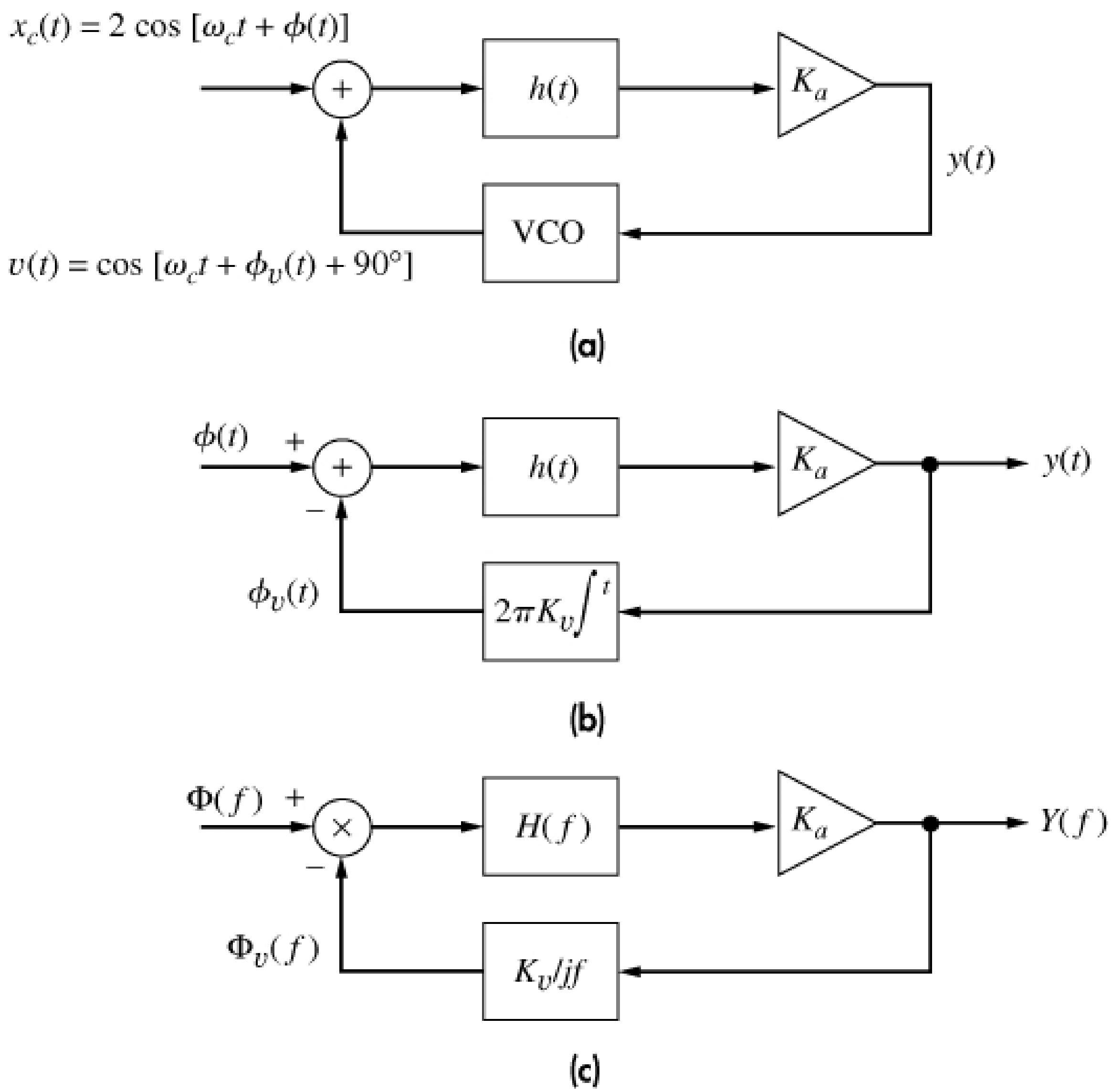


$$\sin\varepsilon_{ss}\cos\varepsilon_{ss} = \tfrac{1}{2}\sin 2\varepsilon_{ss} + \sin 0 \approx \varepsilon_{ss}$$

Frequency synthesizer with fixed and adjustable outputs



Linearized PLL models (a) time domain (b) phase (c) frequency domain

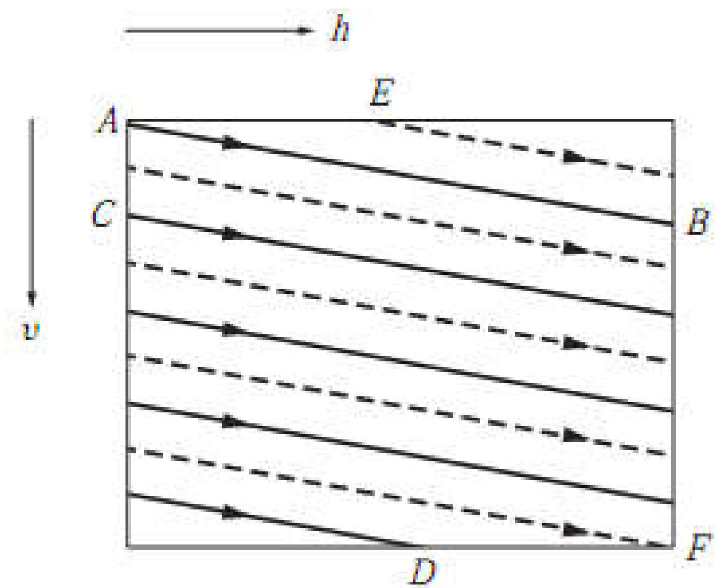


TV transmission

The monochrom intensity:

I(h,v), where h and v are the horizontal and vertical coordinate

Interlaced scanning Raster with two fields



The video signal: $x(t) = I(s_h t, s_v t)$

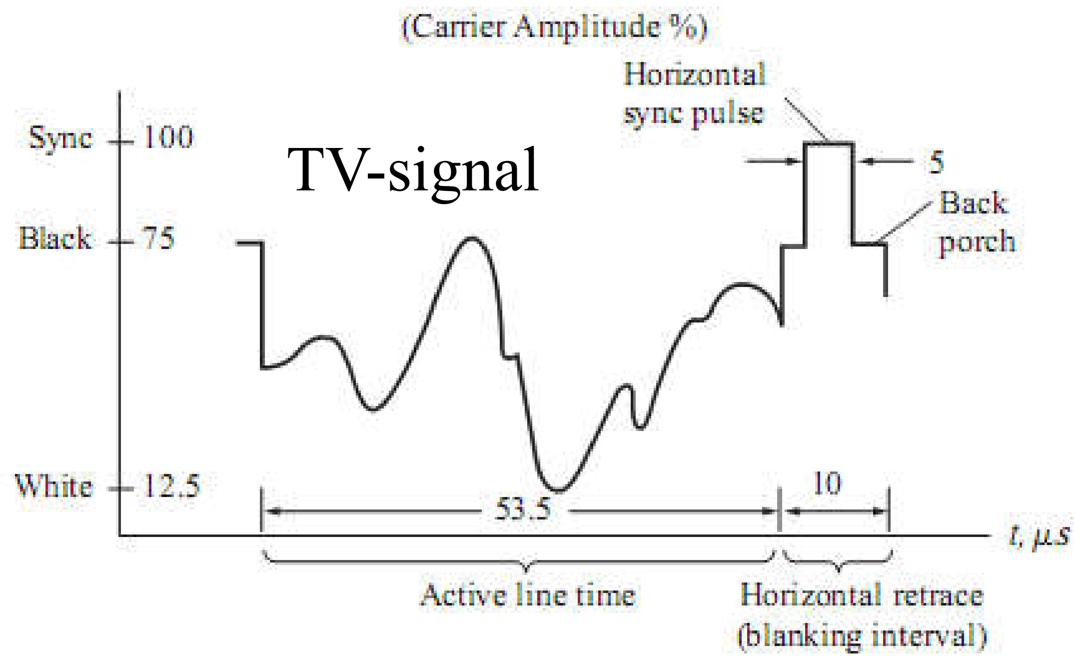
NTSC: National Television System Committee

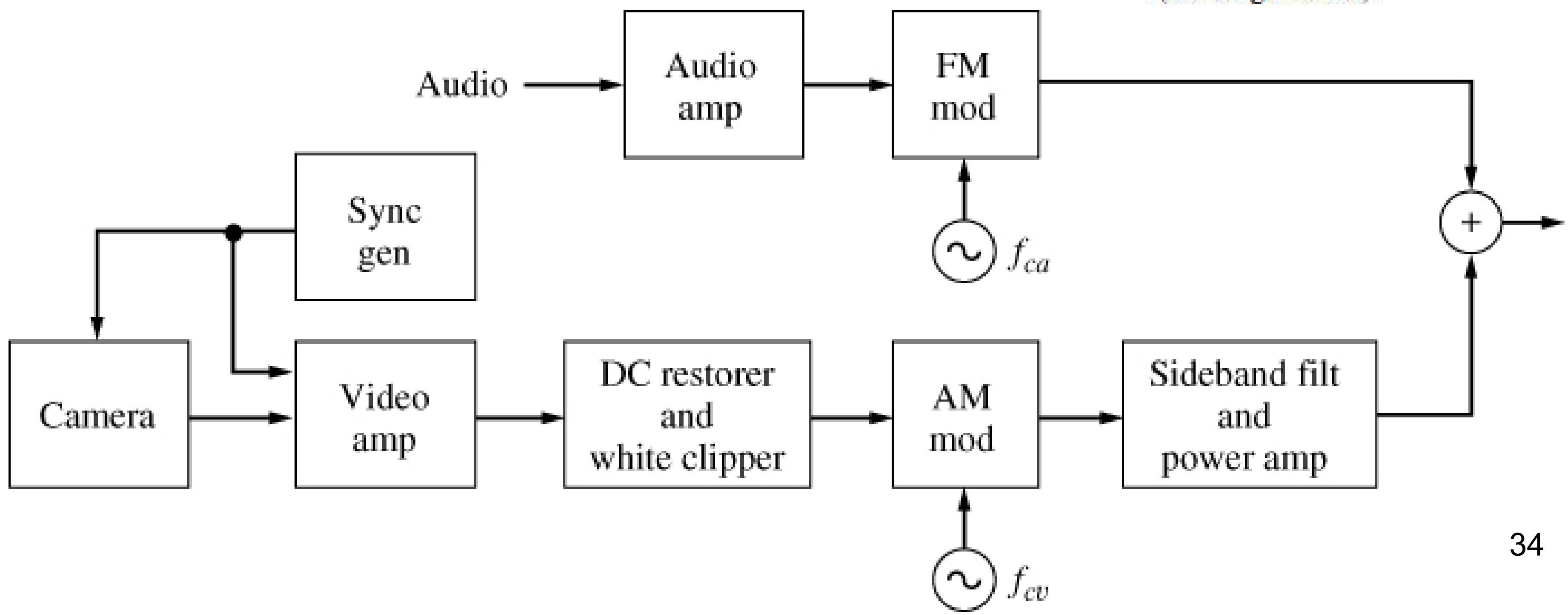
CCIR: International Radio Consultative Committee

PAL: Phase Alternating Line

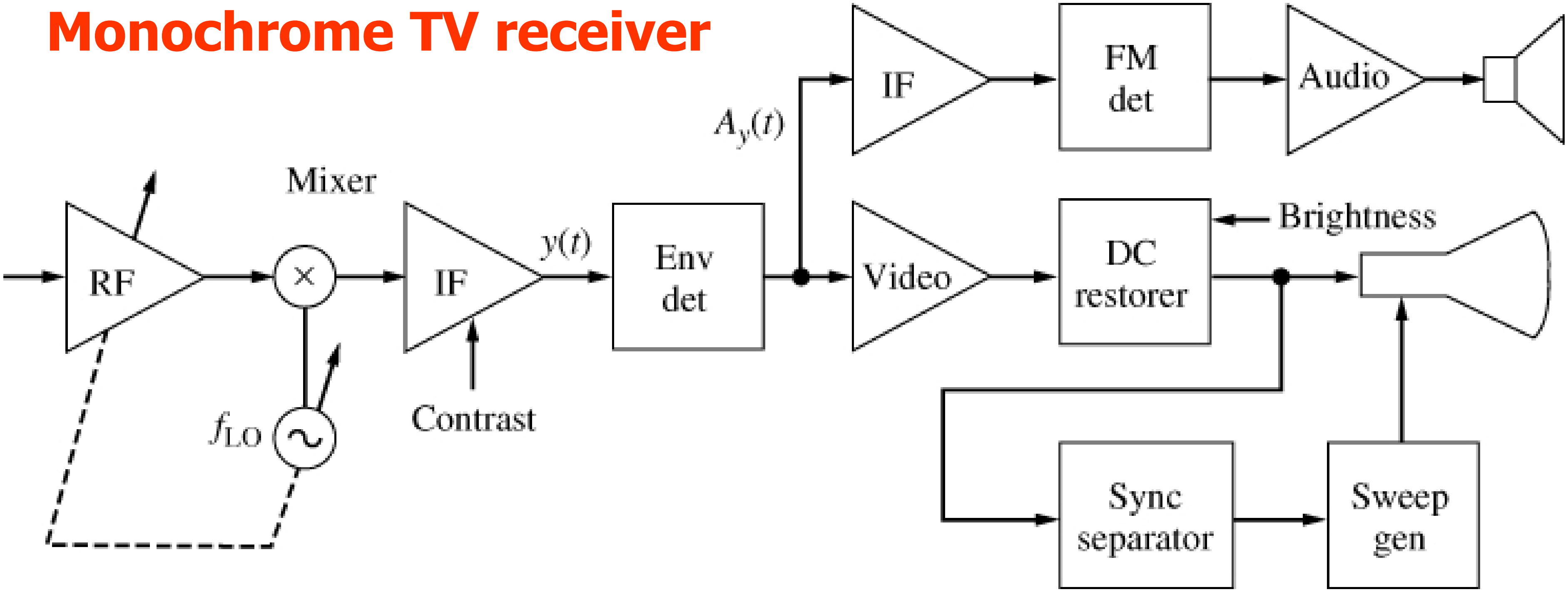
SECAM: Sequentiel Couleur a memoire (Sequencial Color with Memory)

Monochrome TV transmitter



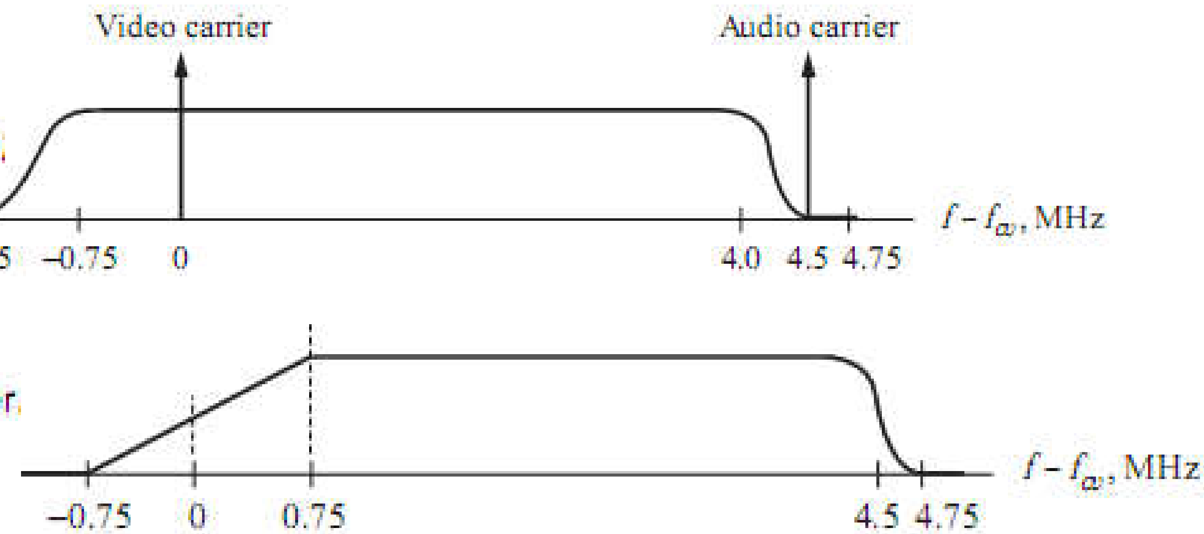


Monochrome TV receiver



(a) Transmitted TV spectrum,

(b) VSB shaping at receiver.



(b)

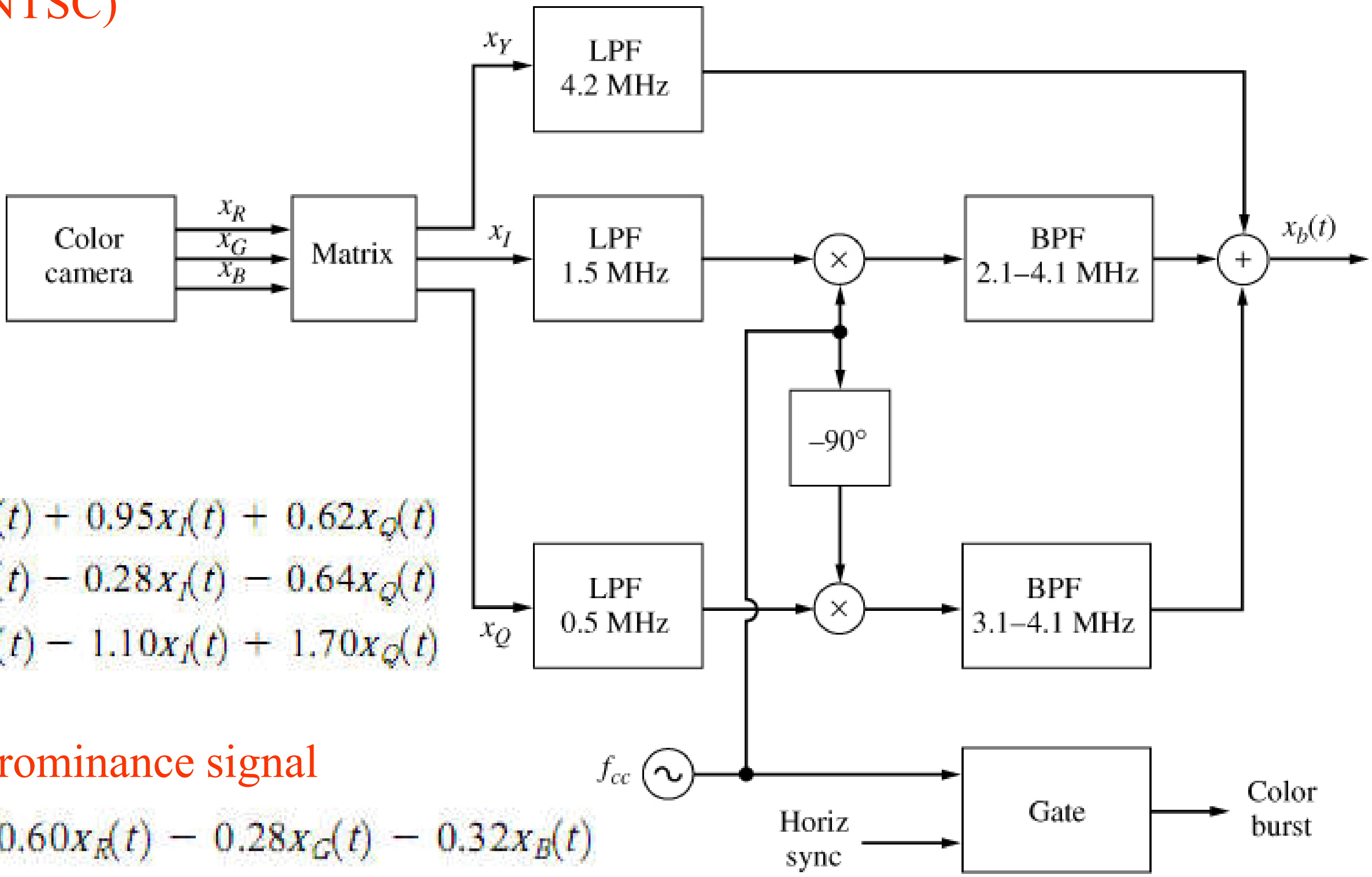
Table 7.4–1 Television system parameters

	NTSC	CCIR	HDTV/USA
Aspect ratio, horizontal/vertical	4/3	4/3	16/9
Total of lines per frame	525	625	1125
Field frequency, Hz	60	50	60
Line frequency, kHz	15.75	15.625	33.75
Line time, μs	63.5	64	29.63
Video bandwidth, MHz	4.2	5.0	24.9
Optimal viewing distance	7H	7H	3H
Sound	Mono/Stereo output	Mono/Stereo output	6 channel Dolby Digital Surround
Horizontal retrace time, μs	10		3.7
Vertical retrace, lines/field	21		45

The aspect ratio $$\frac{n_h}{n_v} = \frac{H}{V}$$

Color subcarrier modulation system in Color TV

The luminance signal (NTSC) $x_Y(t) = 0.30x_R(t) + 0.59x_G(t) + 0.11x_B(t)$

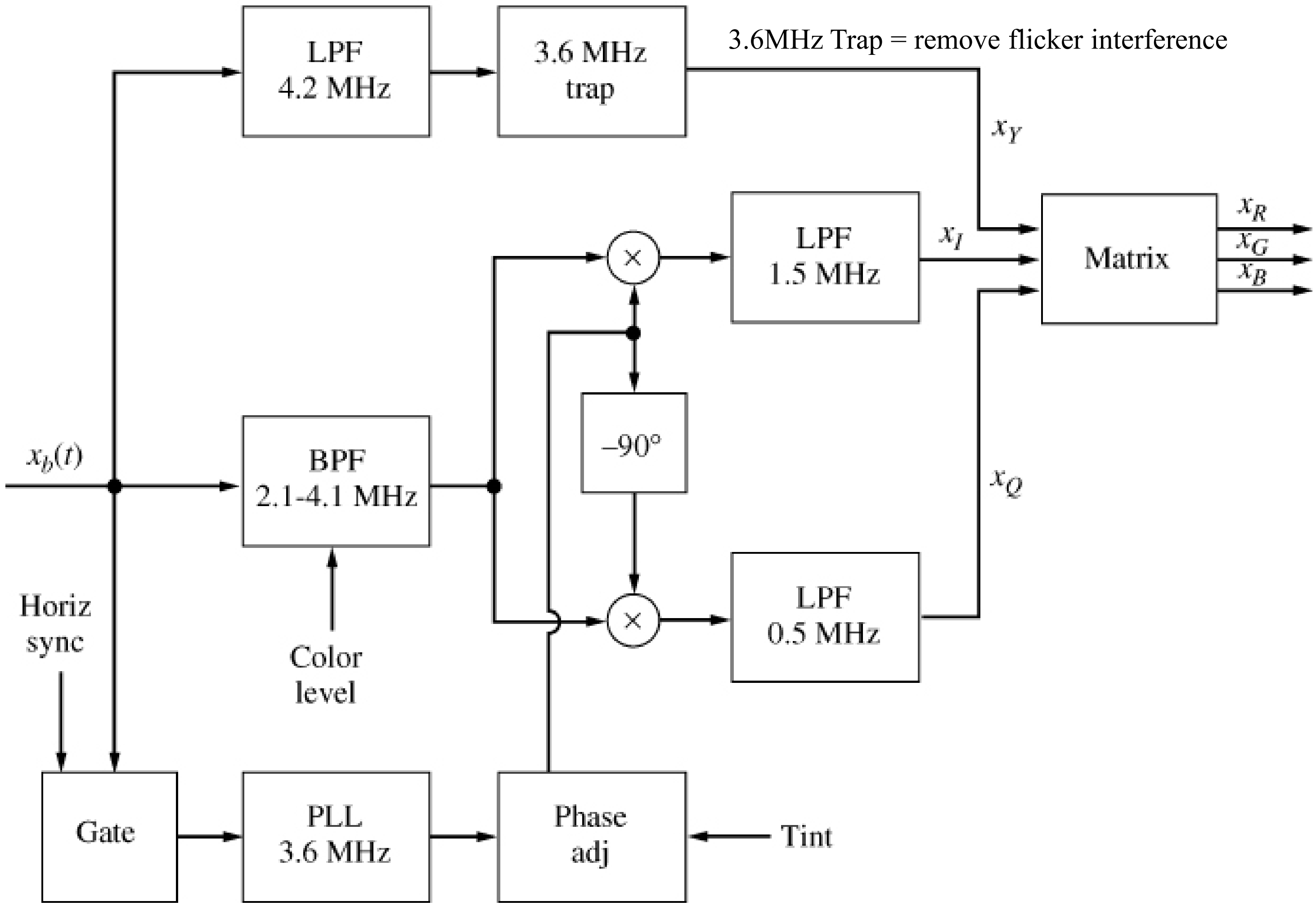


$$x_R(t) = x_Y(t) + 0.95x_I(t) + 0.62x_Q(t)$$
$$x_G(t) = x_Y(t) - 0.28x_I(t) - 0.64x_Q(t)$$
$$x_B(t) = x_Y(t) - 1.10x_I(t) + 1.70x_Q(t)$$

The chrominance signal

$$x_I(t) = 0.60x_R(t) - 0.28x_G(t) - 0.32x_B(t)$$
$$x_Q(t) = 0.21x_R(t) - 0.52x_G(t) + 0.31x_B(t)$$

Color demodulation system



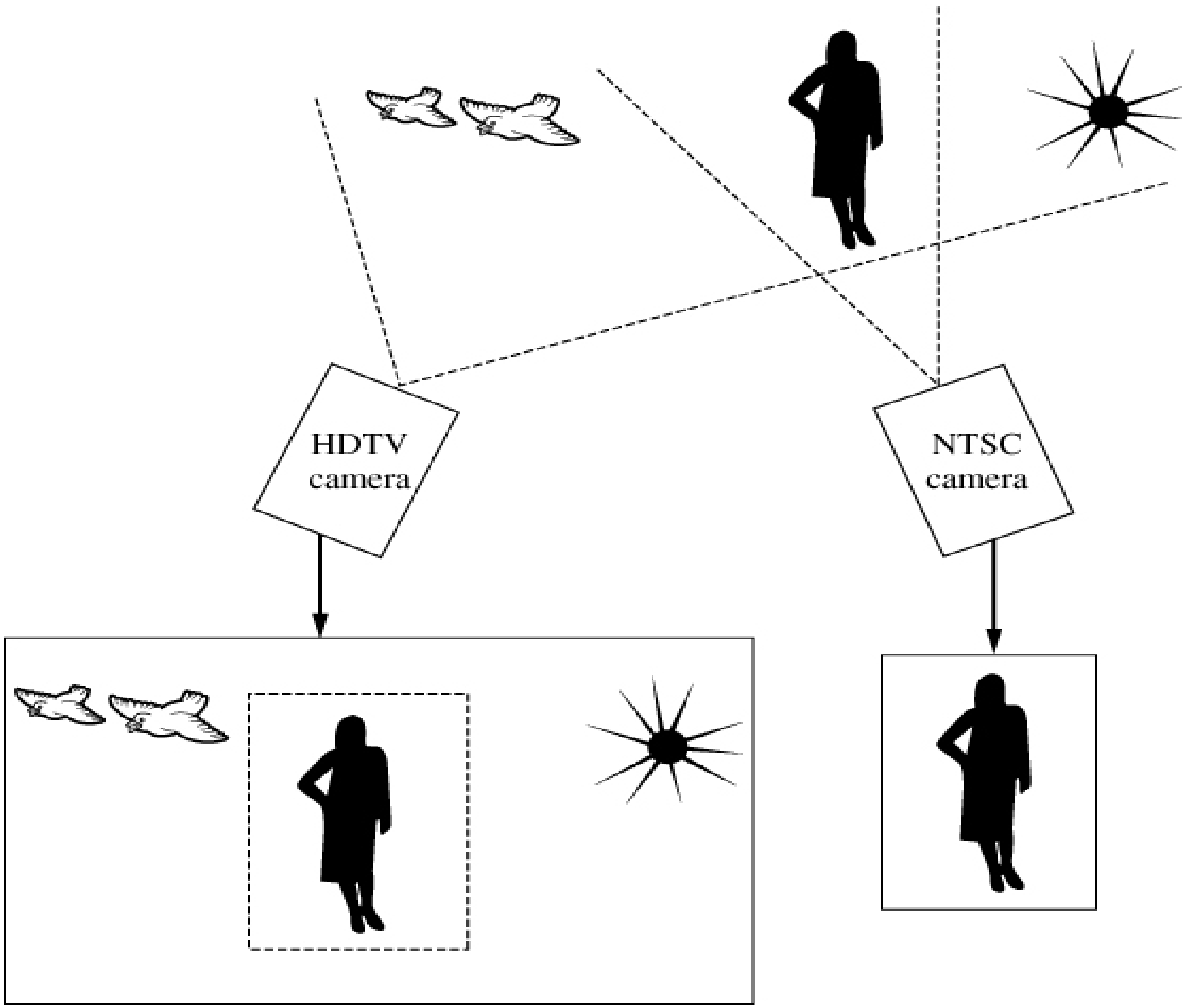
Color vector

$$x_C(t) = x_I(t) + jx_Q(t)$$

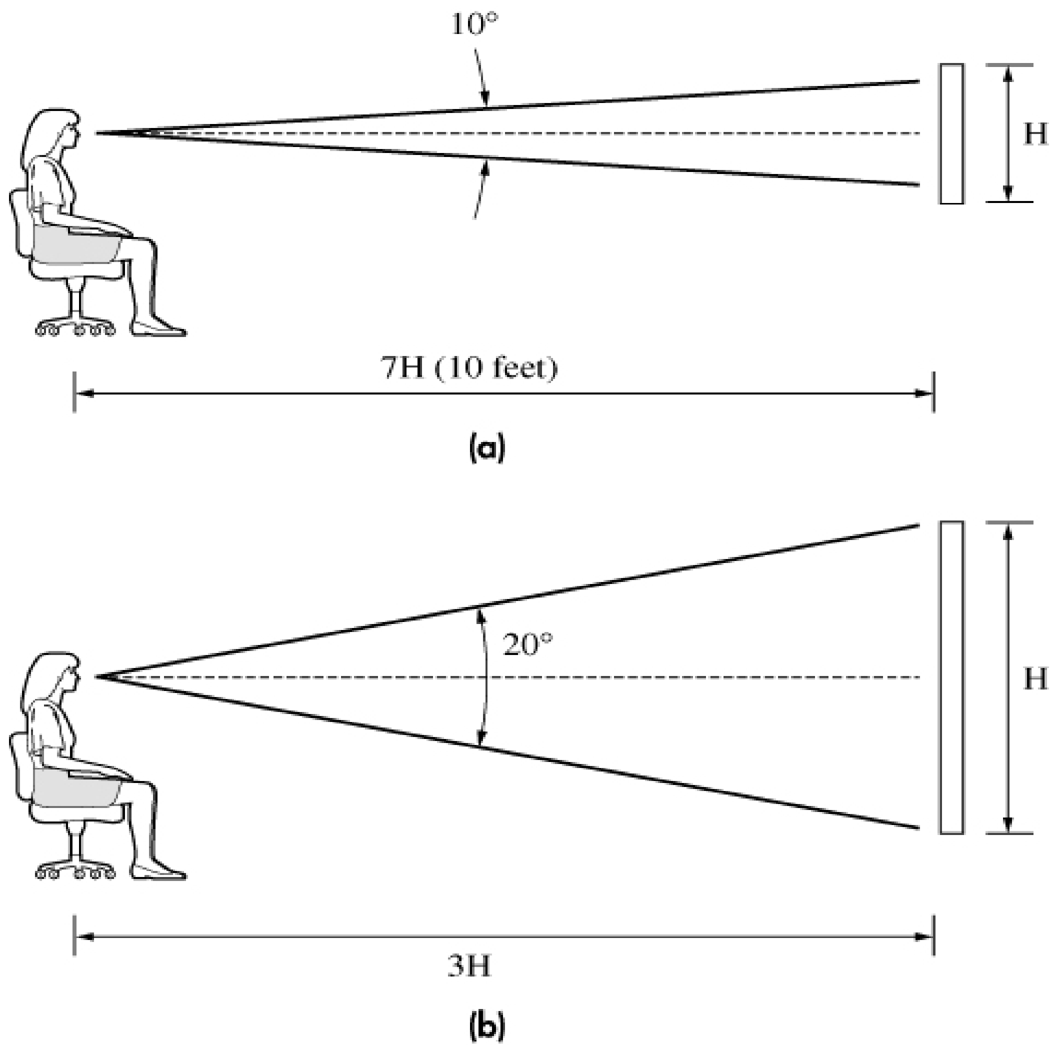
magnitude $|x_c(t)|$ is the color intensity or *saturation*

angle $\arg x_c(t)$ is the *hue*.

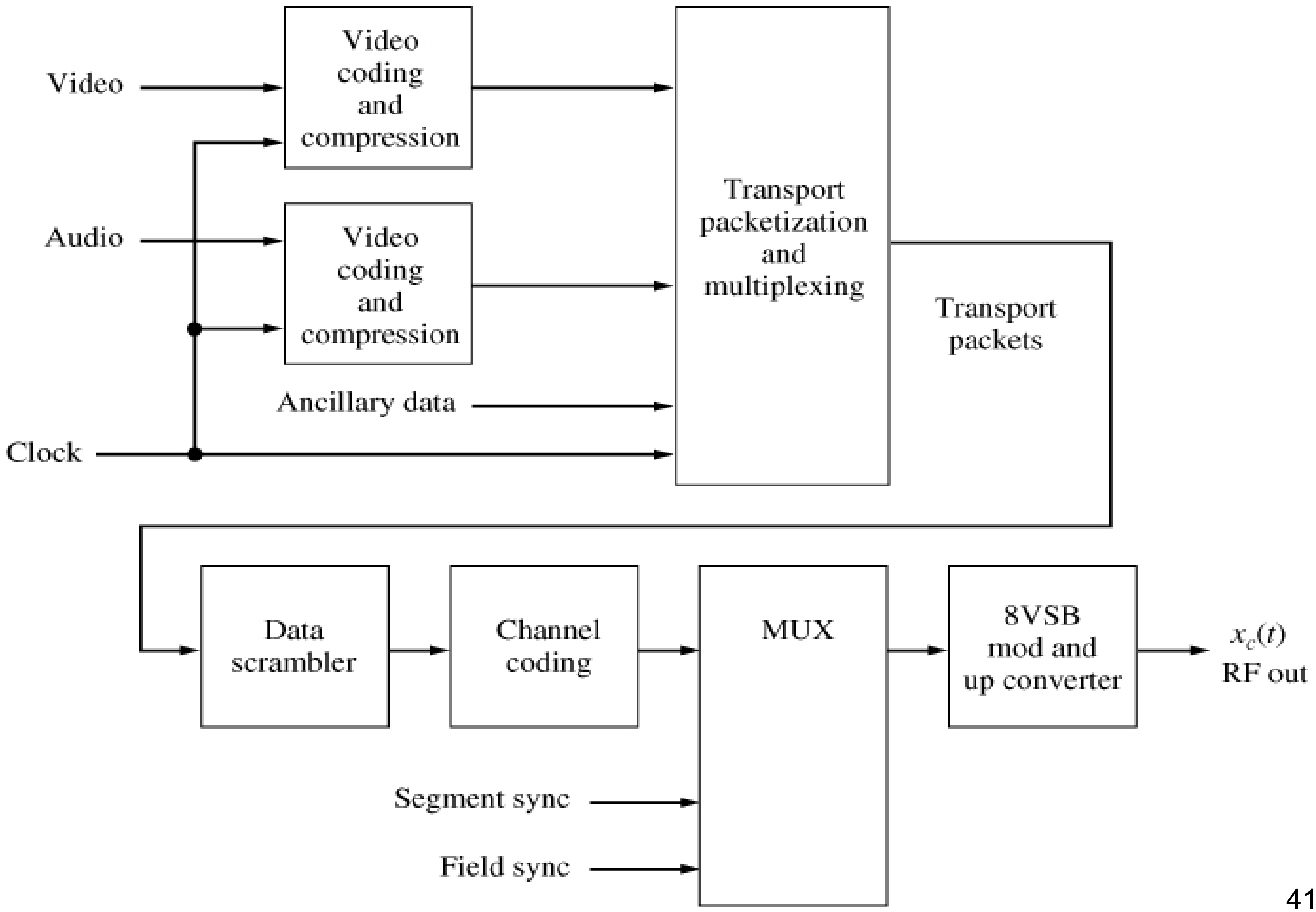
Scene capabilities of conventional NTSC system and HDTV



Viewing angles as a function of distance (a) conventional NTSC (b) HDTV



HDTV transmitter



HDTV receiver