ECSE413B: COMMUNICATIONS SYSTEMS II

Tho Le-Ngoc, Winter 2008

ELEMENTS OF A RADIO TRANSCEIVER

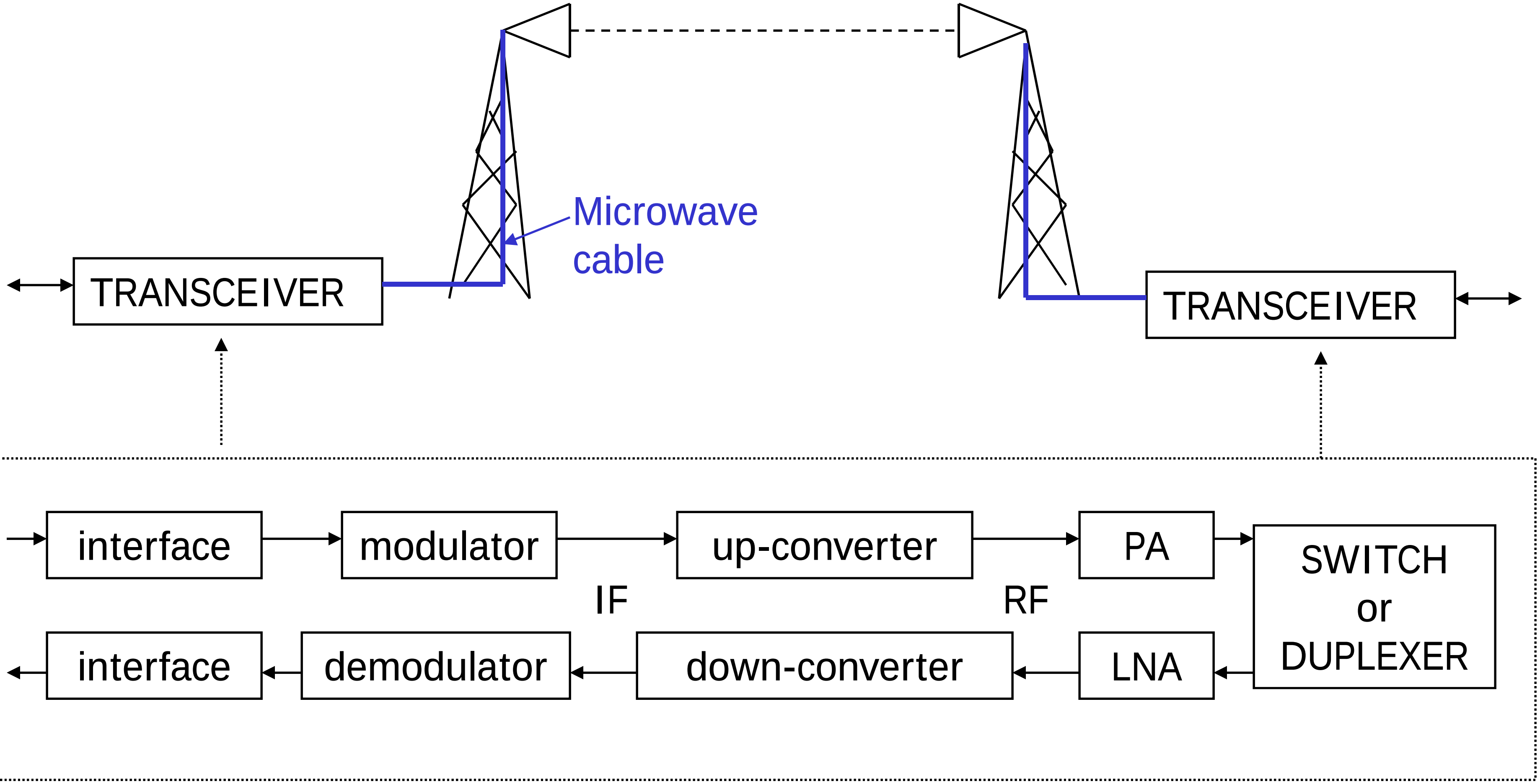
An overview of key elements and characteristics of a radio transceiver:

Power amplifiers & nonlinear distortions,

low-noise amplifiers & noise figures,

antennas,...

A POINT-TO-POINT LINK & DIGITAL MICROWAVE TRANSCEIVER



TRANSCEIVER

Microwave cable

TRANSCEIVER

interface

modulator

up-converter

PA

SWITCH or DUPLEXER

IF

RF

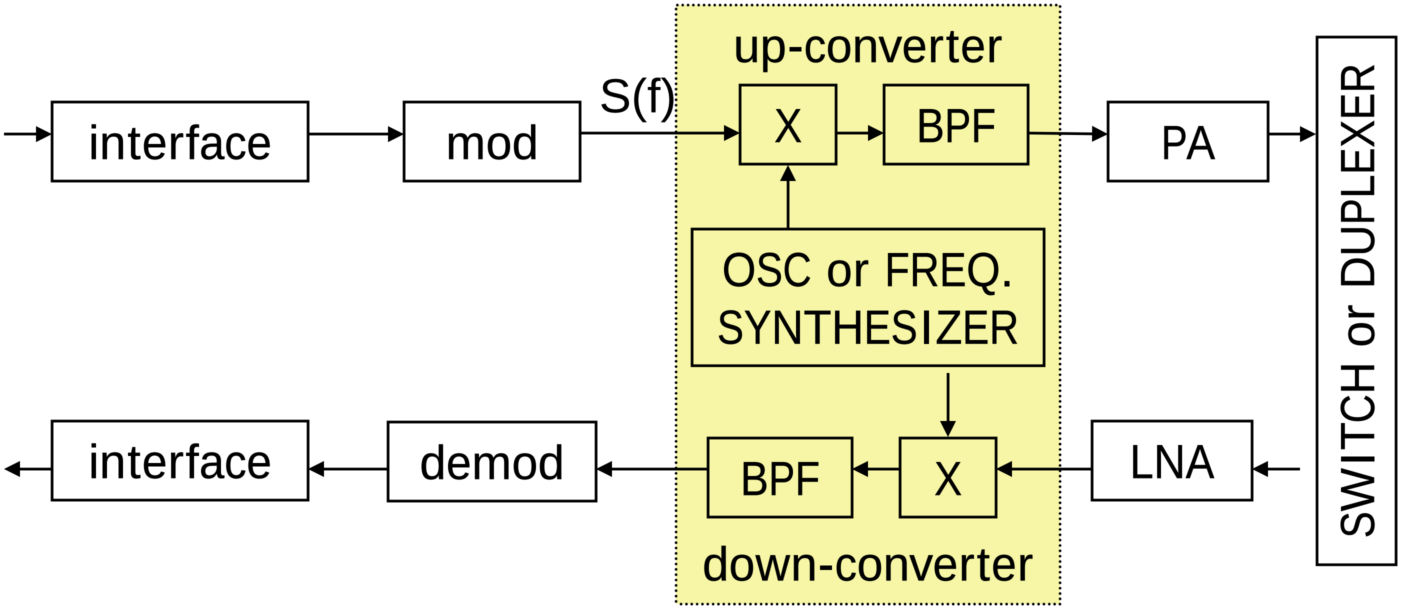
interface

demodulator

down-converter

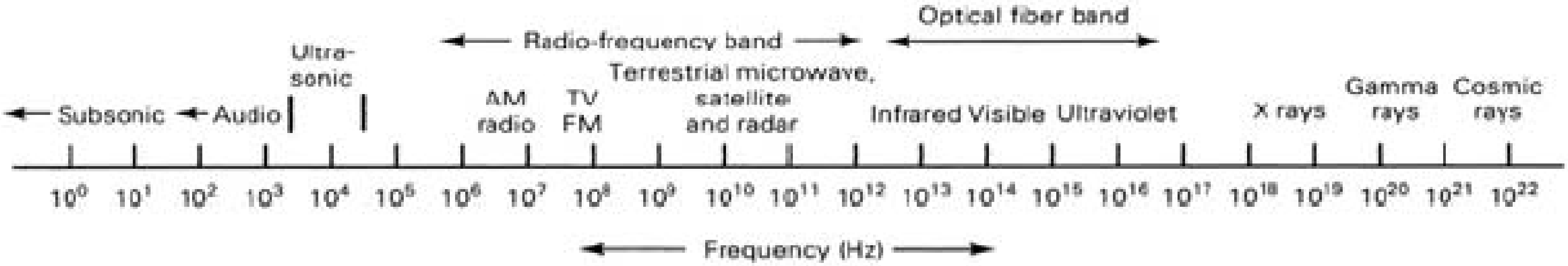
LNA

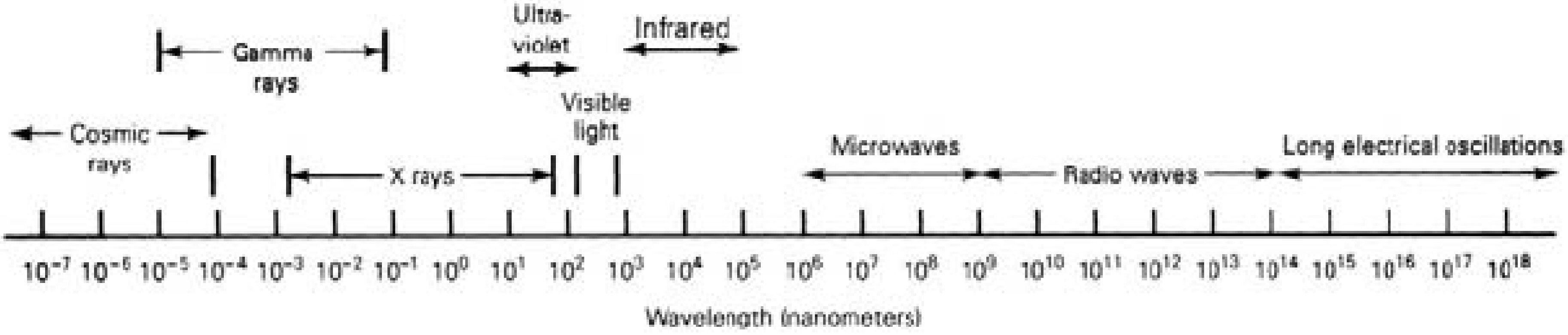
FREQUENCY TRANSLATION:
UP & DOWN CONVERSION



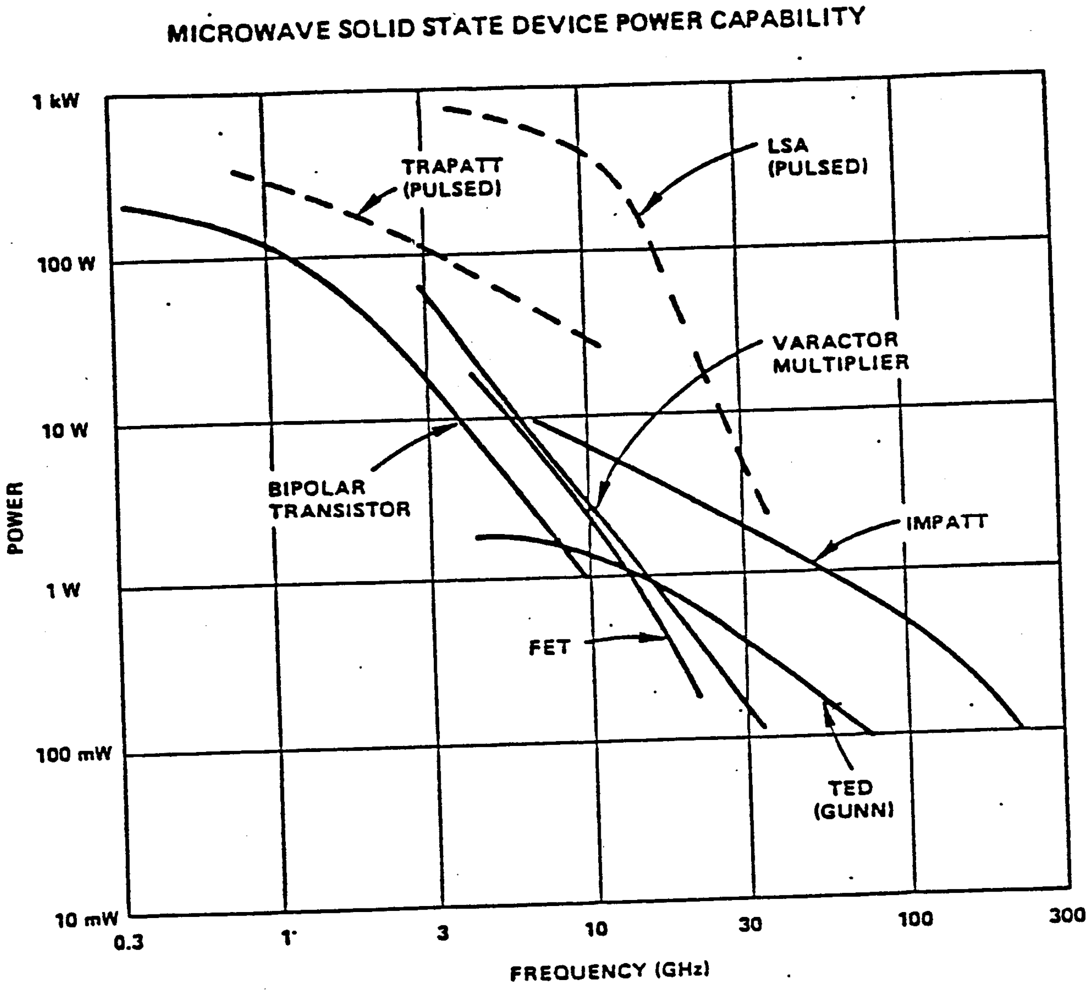
- Modulated signal s(t) has its spectrum S(f) centered at f_0.
- UP-CONVERVERTER: $g(t)=s(t).\cos(2\pi f_A t) \Leftrightarrow G(f)=0.5\{S(f-f_A)+ S(f+f_A)\}$
- Select either $S(f-f_A)$ or $S(f+f_A)$ by filtering, e.g., $S(f+f_A)$ centered at $f_B=f_0+f_A$
- DOWN-CONVERVERTER: $r(t)=g(t).\cos(2\pi f_D t) \Leftrightarrow R(f)=0.5\{G(f-f_D)+ G(f+f_D)\}$
- Select either $G(f-f_D)$ or $G(f+f_D)$ by filtering, e.g., $G(f-f_D)$ centered at $f_c=f_B-f_D$
- Signal is not distorted by frequency translation

ELECTROMAGNETIC SPECTRUM

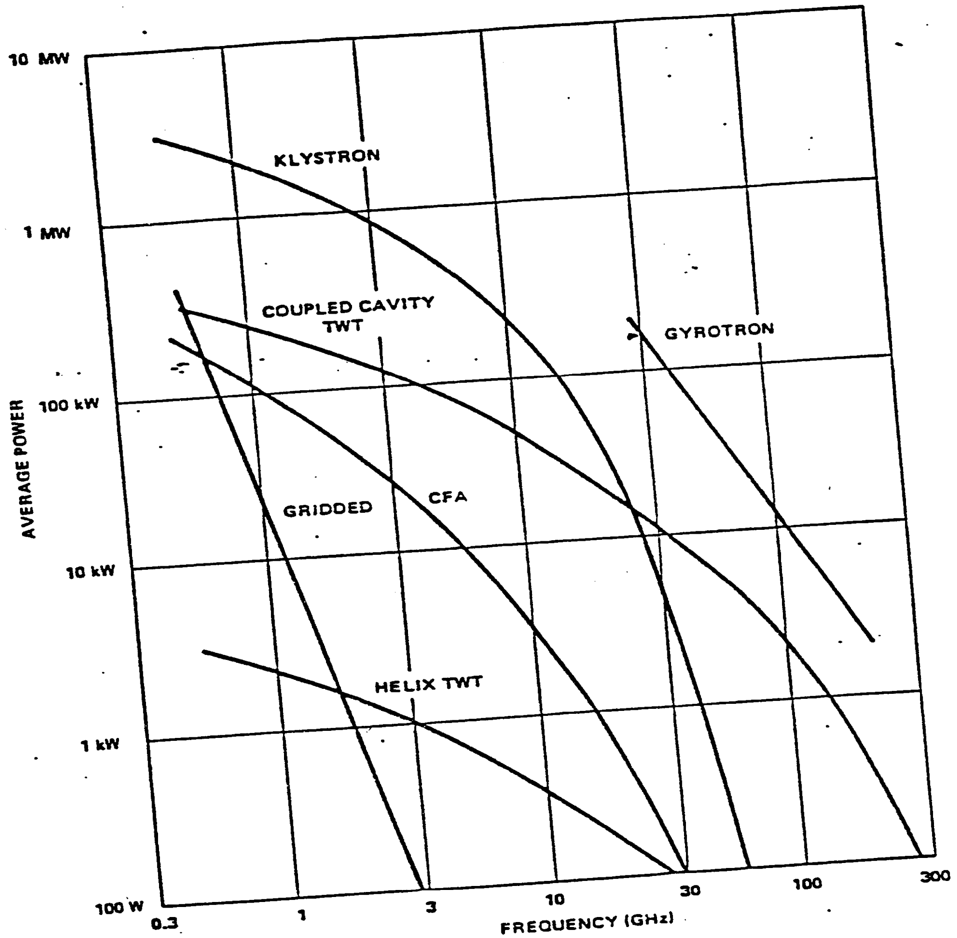




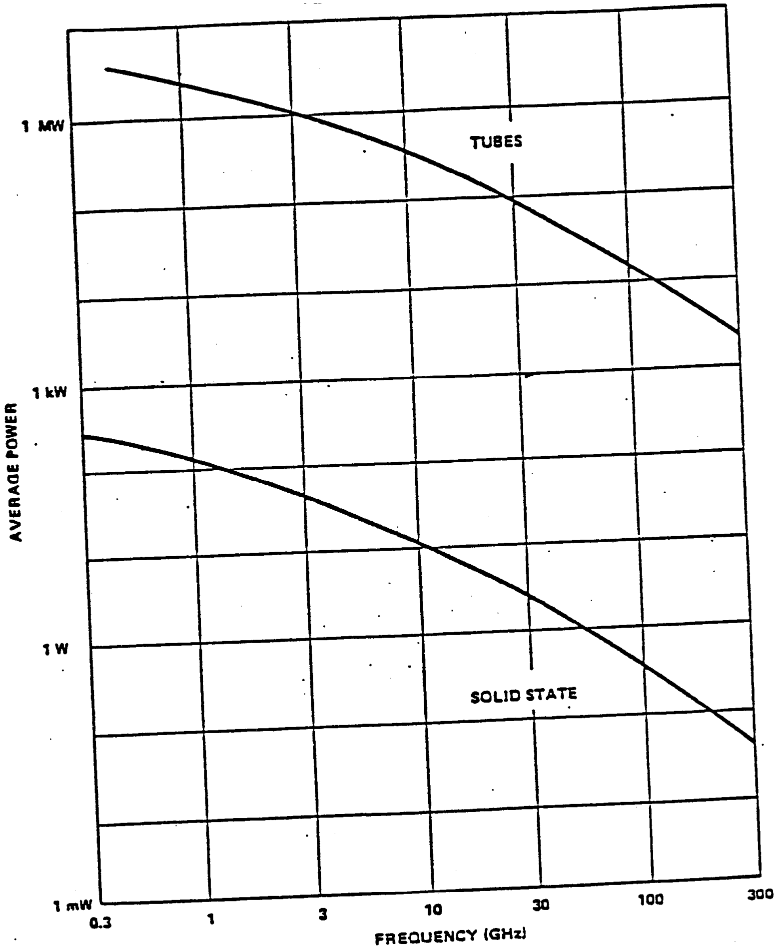
POWER CAPABILITY:
SOLID-STATE POWER AMPLIFIER



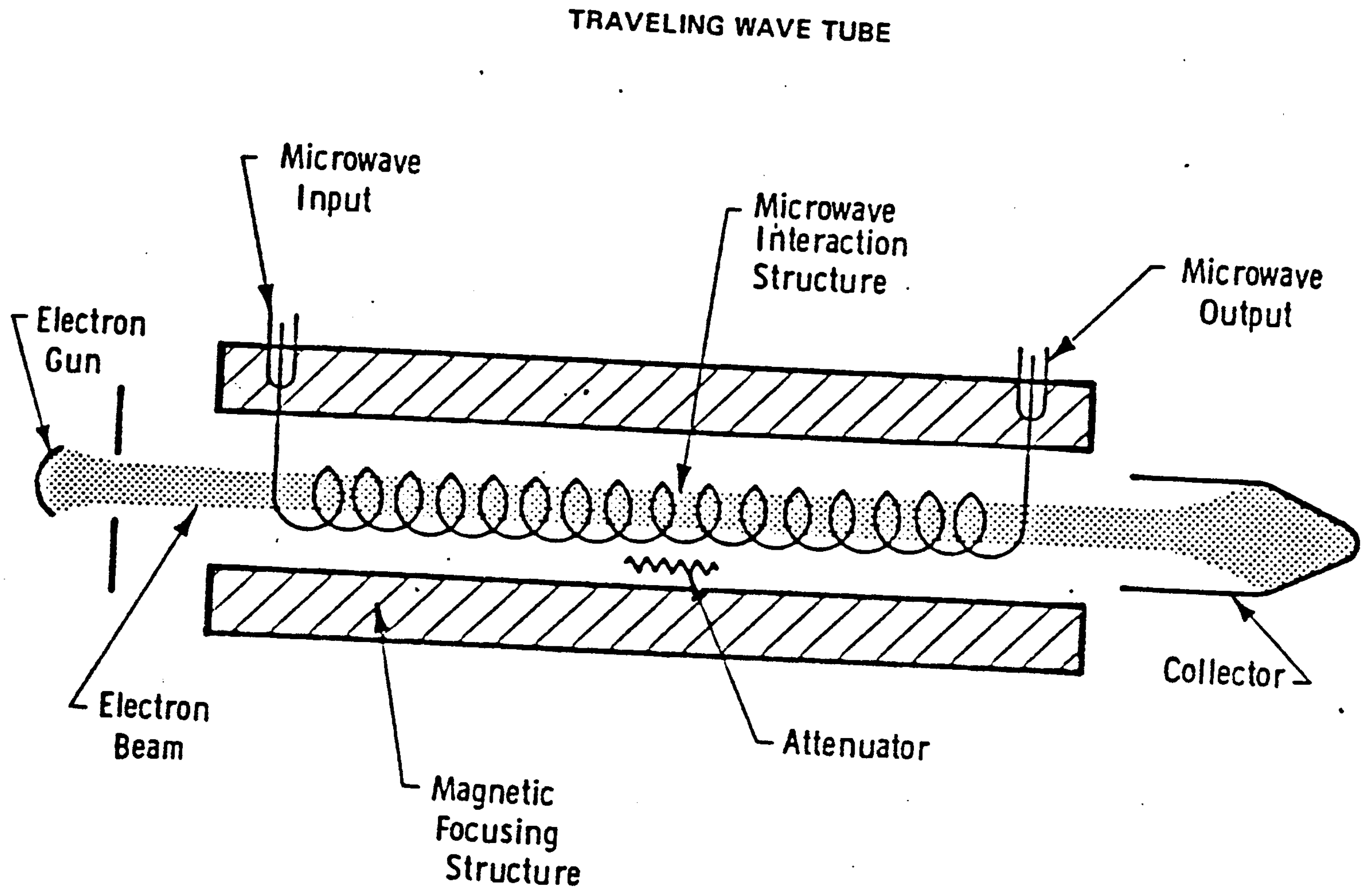
POWER CAPABILITY: MICROWAVE TUBE



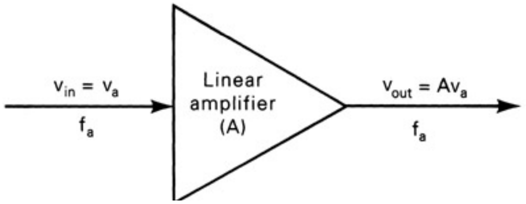
POWER CAPABILITY COMPARISON: SOLID STATE & TUBES



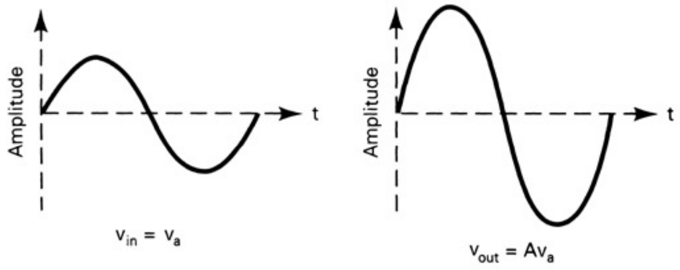
TWT: TRAVELING WAVE TUBE



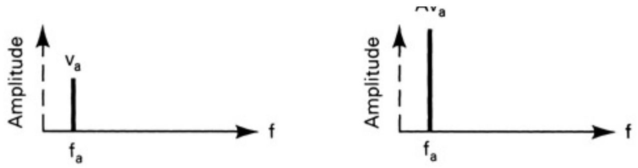
Linear amplification of a single-input frequency



(a) linear amplification

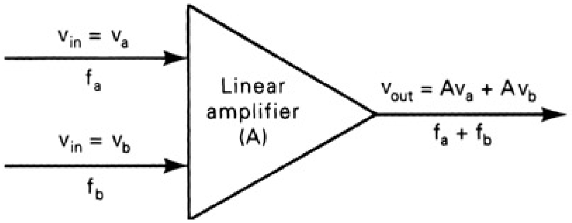


(b) time domain

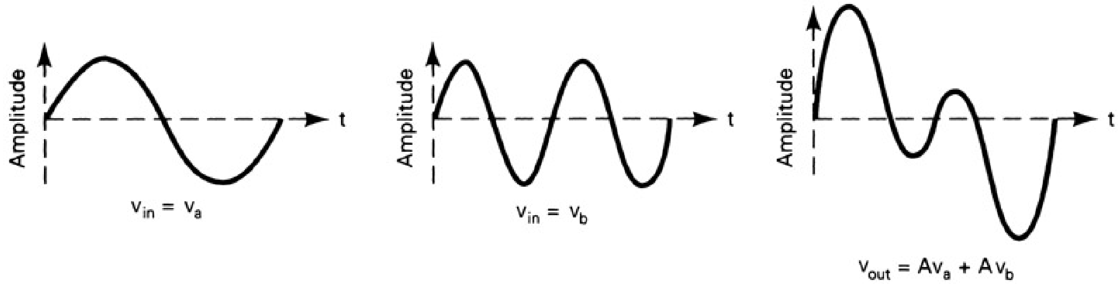


(c) frequency domain

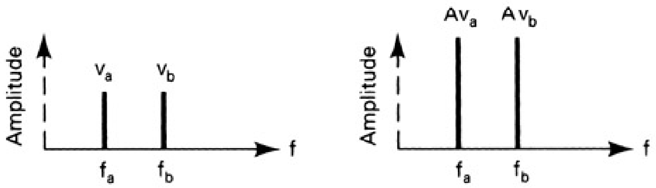
Linear mixing with linear amplification



(a) linear amplification

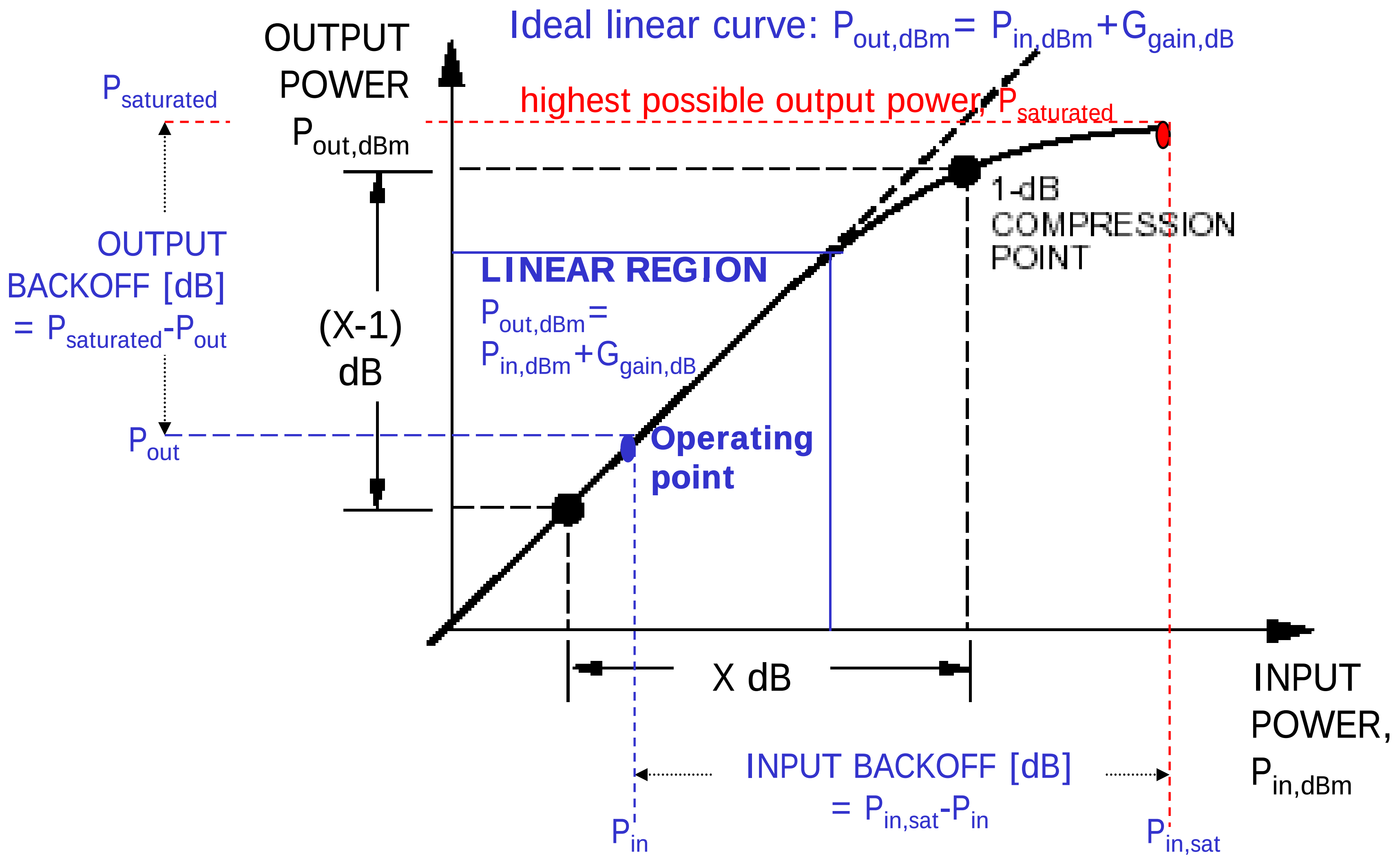


(b) time domain



(c) frequency domain

INPUT/OUPUT POWER CHARACTERISTICS



Ideal linear curve: $P_{out,dBm} = P_{in,dBm} + G_{gain,dB}$

highest possible output power, $P_{saturated}$

OUTPUT POWER $P_{out,dBm}$

$P_{saturated}$

OUTPUT BACKOFF [dB] $= P_{saturated} - P_{out}$

P_{out}

(X-1) dB

LINEAR REGION

$P_{out,dBm} = P_{in,dBm} + G_{gain,dB}$

Operating point

1-dB COMPRESSION POINT

X dB

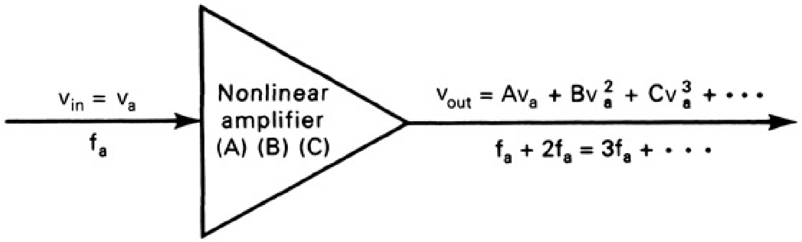
INPUT POWER, $P_{in,dBm}$

INPUT BACKOFF [dB] $= P_{in,sat} - P_{in}$

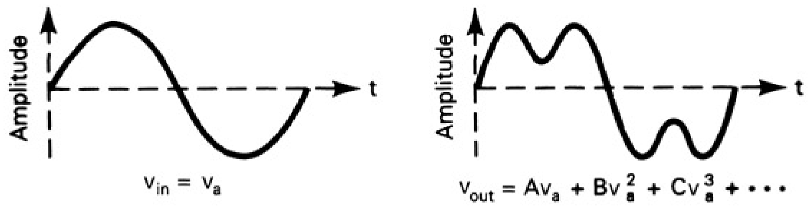
P_{in}

$P_{in,sat}$

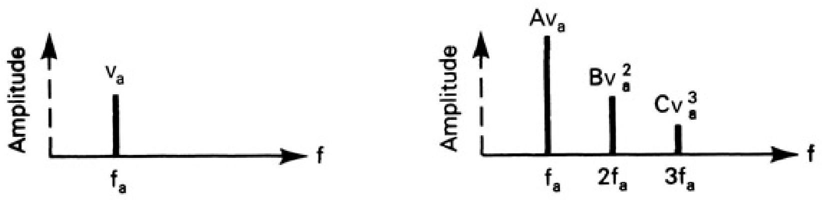
NONLINEAR AMPLIFICATION OF ONE SINGLE-FREQUENCY INPUT



(a) nonlinear amplification

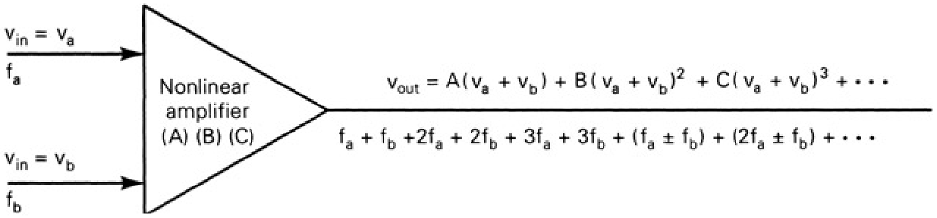


(b) time domain

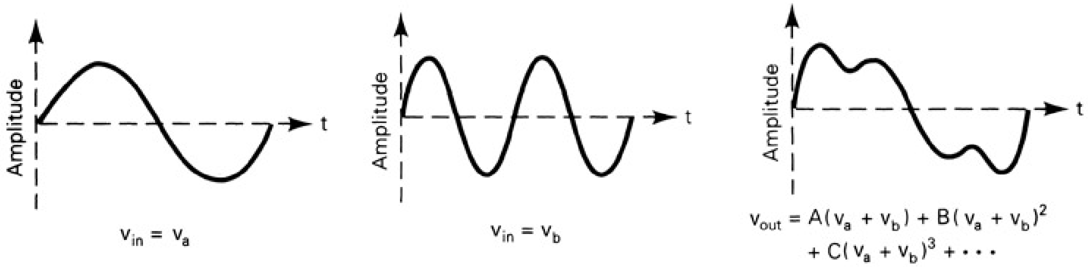


(c) frequency domain

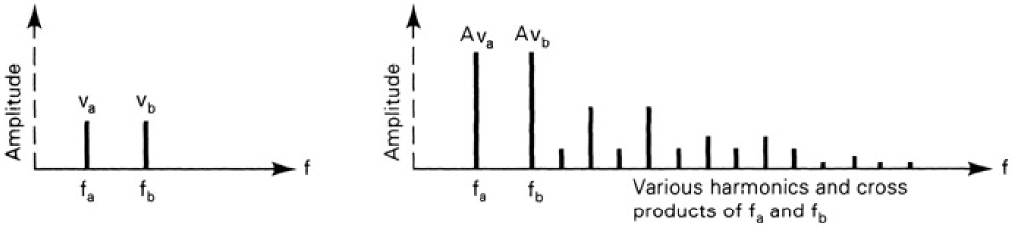
NONLINEAR AMPLIFICATION OF TWO SINE WAVES



(a) nonlinear amplification

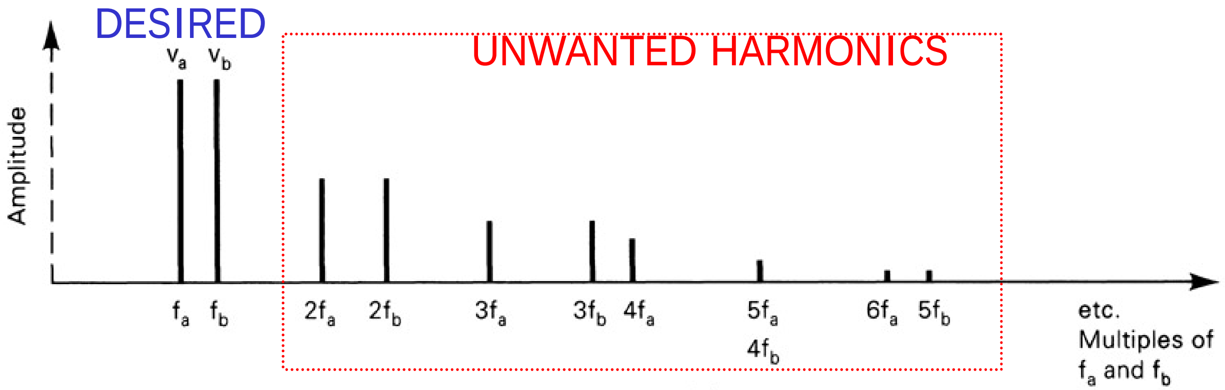


(b) time domain

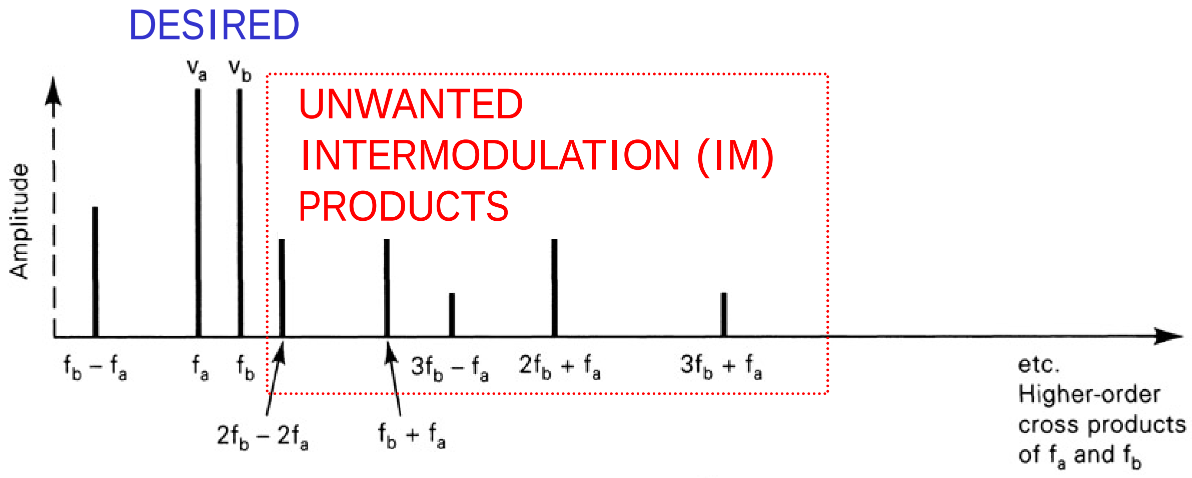


(c) frequency domain

OUTPUT SPECTRUM OF A NONLINEAR AMPLIFIER WITH 2 SINGLE-FREQUENCY INPUTS



(a)



(b)

EFFECT OF NONLINEAR AMPLIFICATION ON MULTICARRIER INPUT

- Input to the amplifier has many carriers, e.g., 3 unmodulated carriers:
  $x(t)=A\cos(\omega_1 t)+B\cos(\omega_2 t)+C\cos(\omega_3 t)$
- quasi-linear amplifier: $y(t)=G_1 x(t)+ G_3\,[x(t)]^3$
- $y(t)=G_1[A\cos(\omega_1 t)+B\cos(\omega_2 t)+C\cos(\omega_3 t)]$
  $+\ G_3[A\cos(\omega_1 t)+B\cos(\omega_2 t)+C\cos(\omega_3 t)]^3$
- $[A\cos(\omega_1 t)+B\cos(\omega_2 t)+C\cos(\omega_3 t)]^3$
  $= A^3 \cos^3(\omega_1 t)+B^3 \cos^3(\omega_2 t)+C^3 \cos^3(\omega_3 t)$
  $+\ 3A^2 B\cos^2(\omega_1 t)\cos(\omega_2 t)+ 3A^2 C\cos^2(\omega_1 t)\cos(\omega_3 t)$
  $+\ 3B^2 A\cos^2(\omega_2 t)\cos(\omega_1 t)+ 3B^2 C\cos^2(\omega_2 t)\cos(\omega_3 t)$
  $+\ 3C^2 A\cos^2(\omega_3 t)\cos(\omega_1 t)+ 3C^2 B\cos^2(\omega_3 t)\cos(\omega_2 t)$
  $+\ 6ABC\cos(\omega_1 t)\cos(\omega_3 t)\cos(\omega_2 t)$

INTERMODULATION PRODUCTS

- $\cos^3(\omega_n t) = 0.75\cos(\omega_n t) + 0.25\cos(3\omega_n t)$, remaining term after filtering: $0.75\cos(\omega_n t)$
- $\cos^2(\omega_n t)\cos(\omega_m t) = 0.5\cos(\omega_m t) + 0.25\cos(\omega_{2n-m} t) + 0.25\cos(\omega_{2n+m} t)$

  remaining terms after filtering: $0.5\cos(\omega_m t) + 0.25\cos(\omega_{2n-m} t)$ where $\cos(\omega_{2n-m} t)$ is an inband intermodulation interferer
- $\cos(\omega_1 t)\cos(\omega_3 t)\cos(\omega_2 t) = 0.25[\cos(\omega_{1+2-3} t) + \cos(\omega_{1-2-3} t) + \cos(\omega_{1-2+3} t + \cos(\omega_{1+2+3} t)]$

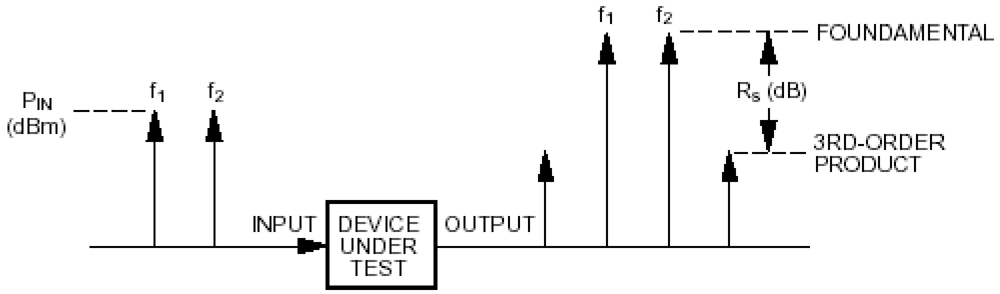
  remaining terms after filtering: $0.25[\cos(\omega_{1+2-3} t) + \cos(\omega_{1-2-3} t) + \cos(\omega_{1-2+3} t]$ where $0.25[\cos(\omega_{1+2-3} t) + \cos(\omega_{1-2-3} t) + \cos(\omega_{1-2+3} t$ are inband intermodulation interferers
- After filtering, $y(t) = a\cos(\omega_1 t) + b\cos(\omega_2 t) + c\cos(\omega_3 t) + \mathrm{IM}$ where

  $\mathrm{IM} = d\cos(\omega_{1+1-2} t) + e\cos(\omega_{1+1-3} t) + f\cos(\omega_{2+2-1} t) + g\cos(\omega_{2+2-3} t) + h\cos(\omega_{3+3-1} t) + i\cos(\omega_{3+3-2} t) + j\cos(\omega_{1+2-3} t) + k\cos(\omega_{1-2-3} t) + l\cos(\omega_{1-2+3} t)$

  are intermod interferers
- 3^{RD} ORDER IM PRODUCTS (IM3) HAS POWER RELATED TO INPUT SIGNAL POWER:

  $P_{IM3,\ dBm} = 3P_{in,\ dBm} + g_{dB}$

3RD-ORDER IM PRODUCTS



2-TONE TEST (TEST WITH 2 SINGLE-FREQ. INPUTS

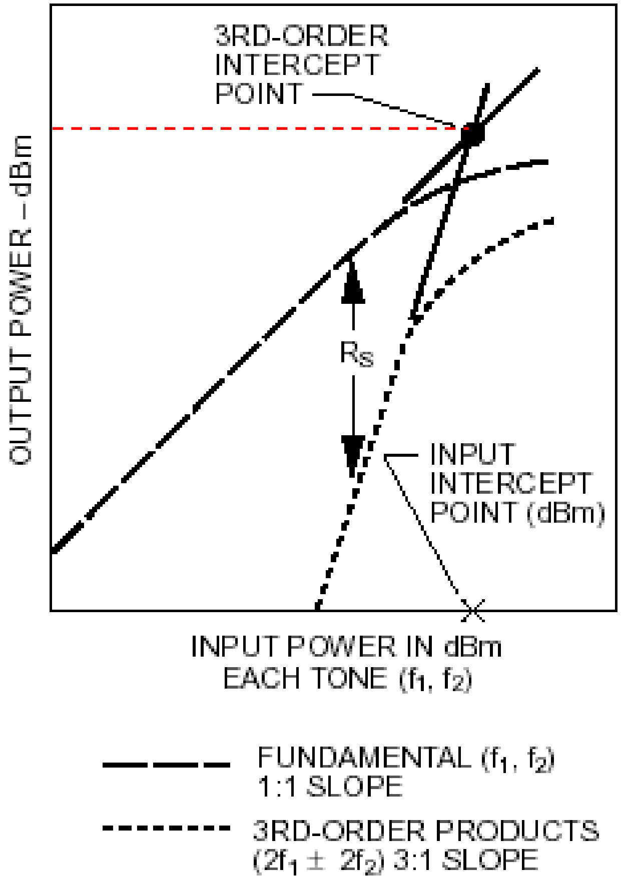
3RD ORDER IM PRODUCTS (IM3) HAS POWER RELATED TO INPUT SIGNAL POWER:

$P_{IM3,\ dBm} = 3P_{in,\ dBm} + g_{dB}$ (IM3 LINE with slope 3)

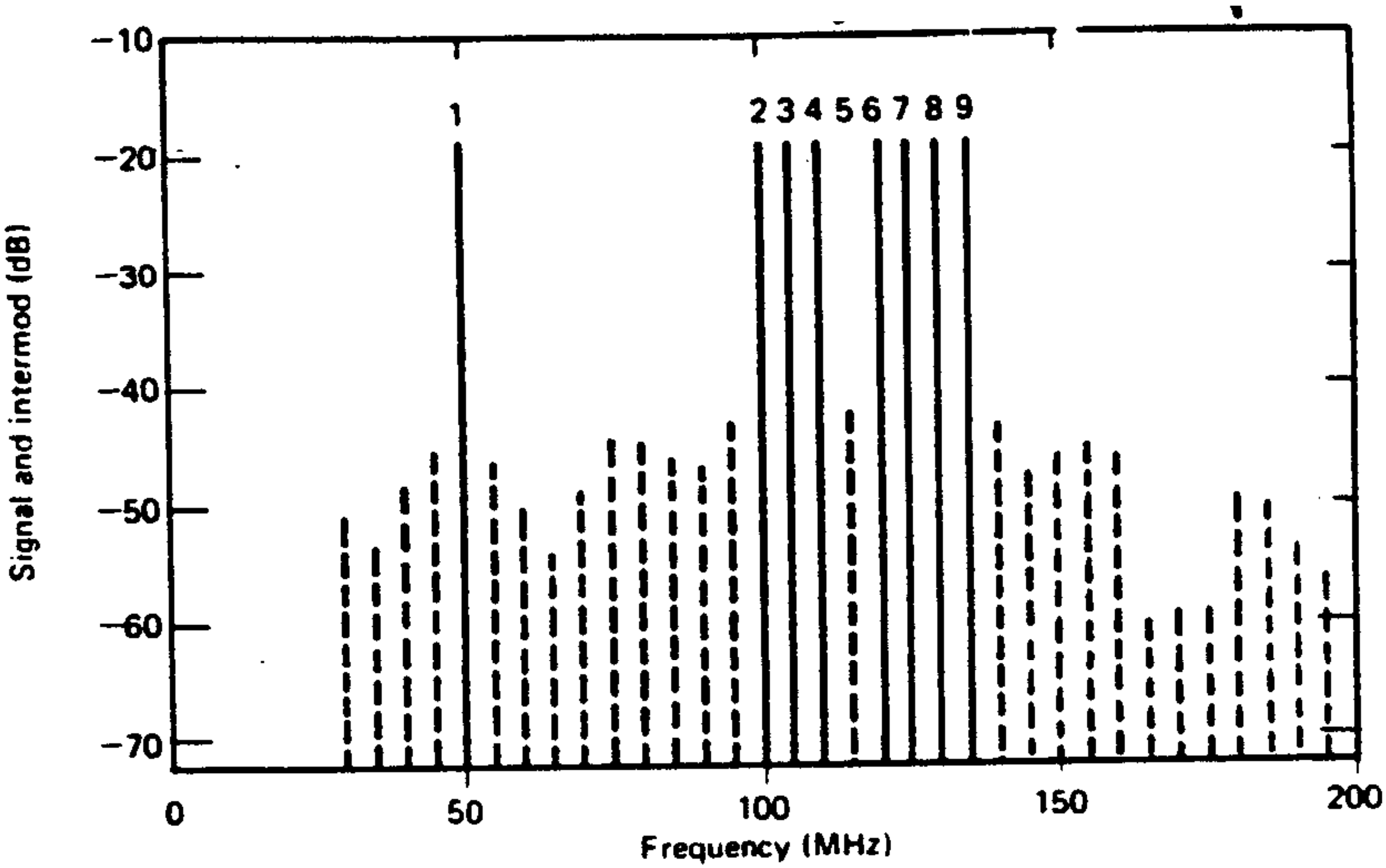
RECALL: INPUT/OUTPUT POWER RELATIONSHIP FOR DESIRED SIGNAL:

$P_{out,dBm} = P_{in,dBm} + G_{gain,Db}$ (I/O LINE with slope 1)

3rd-order intercept point in dBm is the assumed interception of IM3 and I/O LINES



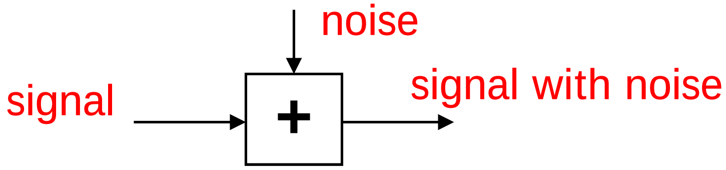
EXAMPLE OF AMPLIFIER OUTPUTS FOR 9 INPUT TONES

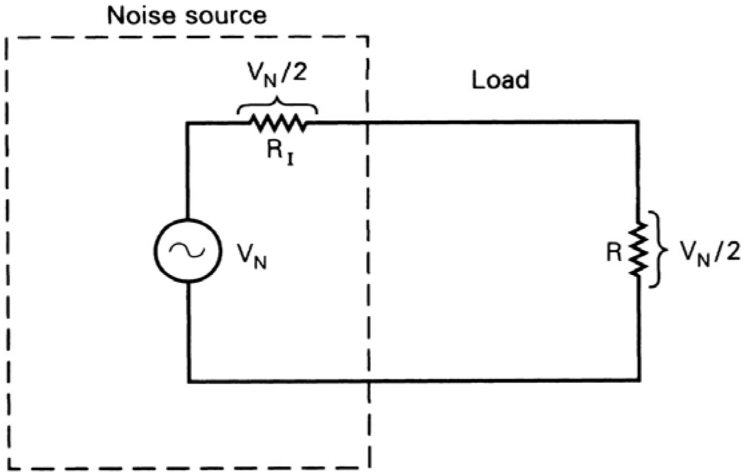


Advanced PA Technologies

- Ultra Linear Power Amplifiers
- PAs are potentially 50 - 70% of future base station cost: Aim is to develop technologies for dramatically lower cost
- Digital Pre-distortion compensates for PA non-linearities:
    - Enabled by accurate modelling of power devices
    - “RF” Feed-Forward is replaced by “Digital Pre-Distortion”
    - DSP-based algorithms for adaptive compensation
    - “Digital” based correction implementation leads to lower cost & high efficiency

THERMAL NOISE IN RECEIVER





Thermal noise produced by random motion of charged particles (e.g., electrons) has a Gaussian distribution and a power spectral density (PSD): $S_n(f)=h|f|/\{\exp(h|f|/kT)-1\}$ W/Hz

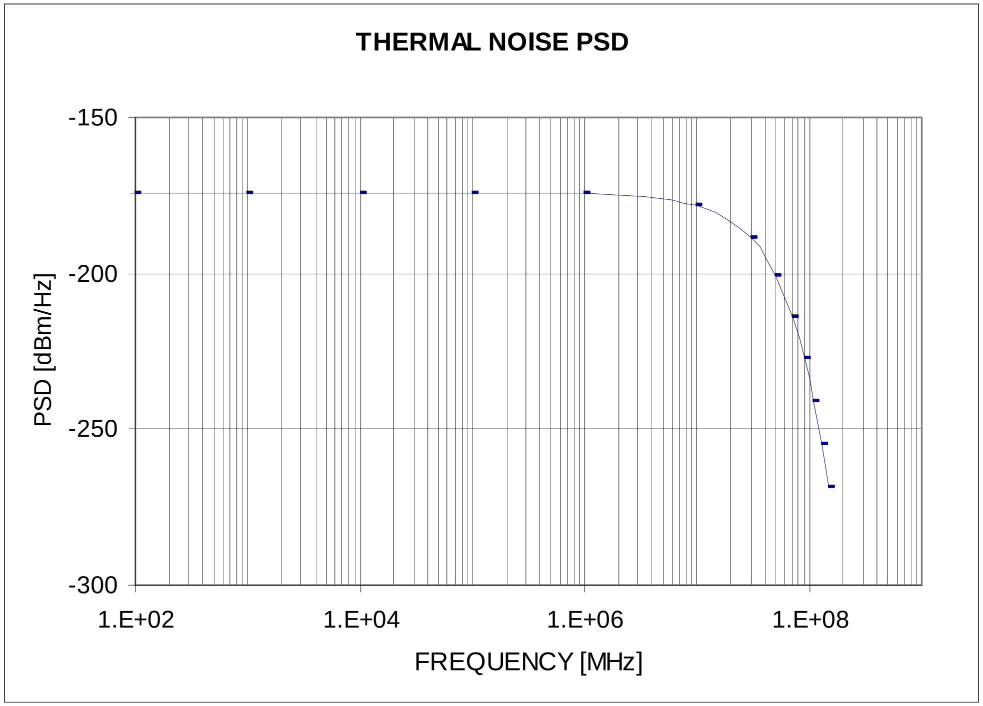
where k=1.38E-23 Joules/°K (Boltzman's constant)

h=6.62E-34 Joules.sec (Plank's constant), °K= 273+ °C

For $|f|<0.1kT/h$ (about 1E12 Hz),

@ room temperature (290°K)

$$S_n(f) \approx kT=-174\text{dBm/Hz}$$



CONCEPTS OF NOISE FACTOR,
NOISE FIGURE:

IDEAL, NOISELESS AMPLIFIER:

Input: $s_i(t)+n_i(t)$

Output: $a_p\{s_i(t)+n_i(t)\}$

Output signal part: $a_p s_i(t)$

Output noise part: $a_p n_i(t)$

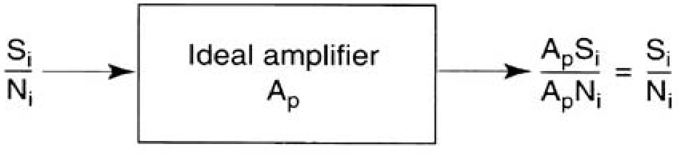
a_n: voltage gain, $A_n=a_n^2$: power gain

S_i: input signal power

N_i: input noise power

$S_o = A_n S_i$: output signal power

$N_o = A_n N_i$: output noise power



(a)

S_i/N_i: input SNR_{in}

$S_o/N_o= A_nS_i/A_nN_i$: output $SNR_{out}= SNR_{in}$

AMPLIFIER WITH INTERNAL NOISE:

Input: $s_i(t)+n_i(t)$

Output: $a_p\{s_i(t)+n_i(t)\}+n_d(t)$

Output signal part: $a_p s_i(t)$

Output noise part: $a_p n_i(t)+n_d(t)$

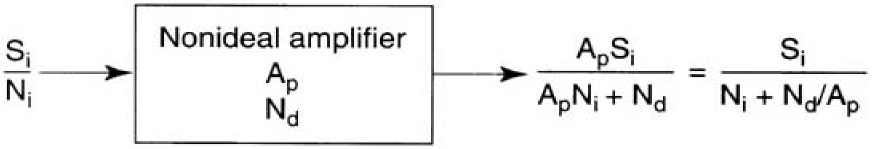
a_n: voltage gain, $A_n=a_n^2$: power gain

S_i: input signal power

N_i: input noise power, N_d: internal noise power

$S_o = A_n S_i$: output signal power

$N_o = A_n N_i+N_d$: output noise power



(b)

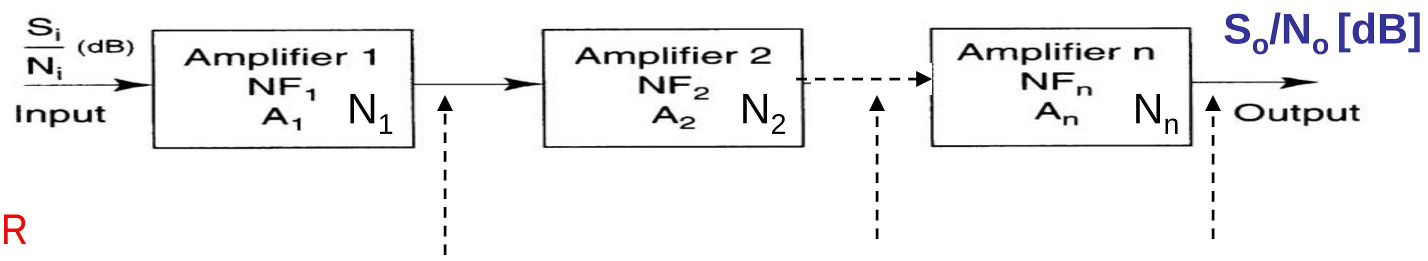
S_i/N_i: input SNR_{in}

$S_o/N_o= A_nS_i/(A_nN_i+N_d)$: output $SNR_{out} < SNR_{in}$

$[S_o/N_o]=[S_i/N_i].[1+N_d/N_iA_p]^{-1}= S_i/N_i].[F\ ]^{-1}$where $F=1+N_d/N_iA_p =[S_i/N_i]/\ [S_o/N_o]$, >1

- F: **noise factor** indicating the factor of SNR degradation at the amplifier output
- **noise figure** $NF_{dB}=10\log_{10}(F)= SNR_{in,dB}- SNR_{out,dB}$

NOISE FACTOR, NOISE FIGURE OF CASCADED AMPLIFIERS:



SIGNAL POWER				
	S_i	A_1S_i	$A_2 A_1S_i$	$S_o=S_i(A_1A_2...A_n)$,
NOISE POWER				
	N_i	$A_1N_i+N_1$	$A_2 (A_1N_i+N_1)+N_2$	N_o

$N_o=N_n+N_{n-1}A_n+N_{n-2}A_{n-1}A_n+...+N_2\ A_nA_{n-1}...A_3+N_1\ A_nA_{n-1}...A_2+N_i\ A_nA_{n-1}...A_2\ A_1$

$N_o=N_i(A_n...A_2\ A_1)\{F_1+(F_2-1)/A_1+(F_3-1)/(A_1A_2)+...+(F_n-1)/(A_1A_2...A_{n-1})\}= N_i(A_n...A_2\ A_1)F_{overall}$

where $F_{overall}= \{F_1+(F_2-1)/A_1+(F_3-1)/(A_1A_2)+...+(F_n-1)/(A_1A_2...A_{n-1})\}$

$F_{overall}=[S_i/N_i]/\ [S_o/N_o]$, and $SNR_{out,dB}=SNR_{in,dB}-(NF_{overall,dB})$ where $NF_{overall,dB}=10\log_{10}(F_{overall})$

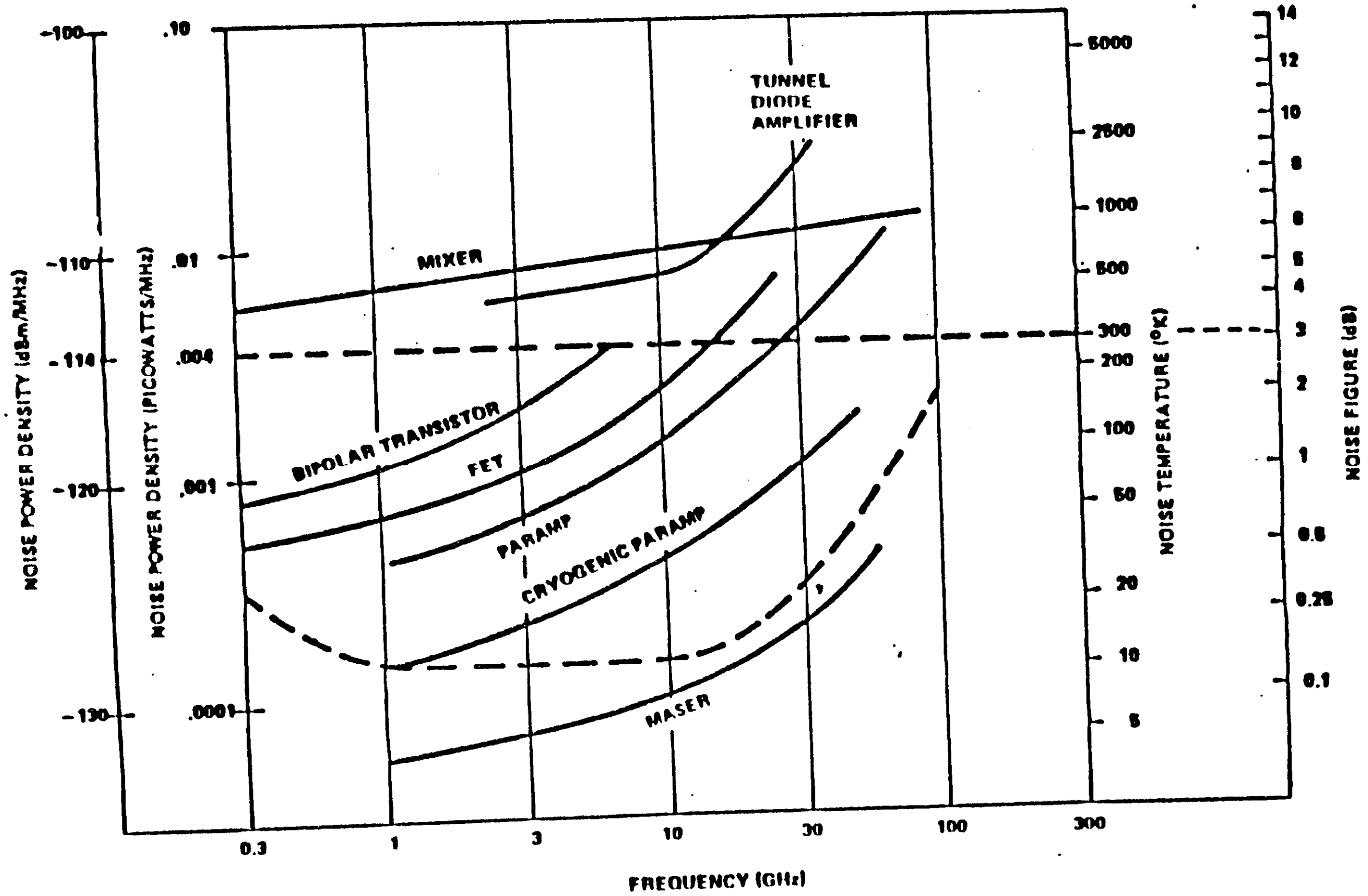
From $F_{overall}= \{F_1+(F_2-1)/A_1+...+(F_n-1)/(A_1A_2...A_{n-1})\}$ it is clear that if A_1 is sufficiently large then F_1 is dominant (i.e., contributions of $F_2,...,F_n$ are small)
Therefore, in a receiver, the front-end amplifier is a **low-noise** amplifier, i.e., with **small F_1 and large A_1**

Example: 3 stages with **A_1=30dB**, $A_2=A_3$=10dB and **NF_1=3dB**, NF_2=8dB, NF_3=10dB

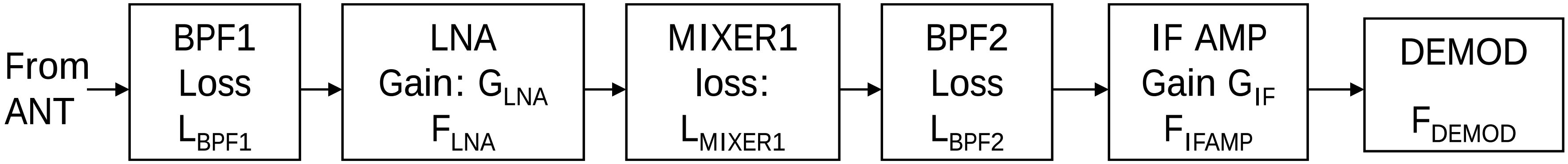
$F_{overall}= F_1+(F_2-1)/A_1+(F_3-1)/(A_1A_2)=10^{3/10}+(10^{8/10}-1)/10^{30/10}+(10^{10/10}-1)/10^{40/10}$

$=10^{3/10}+(5.31E-3)+(9E-4)=2.001=3.013\text{dB}$

NOISE PERFORMANCE OF LNA’s



RECEIVER: OVERALL NOISE FACTOR



For a matched-impedance passive component, its noise factor = insertion loss

Overall gain from input of BPF1 to input of DEMOD:

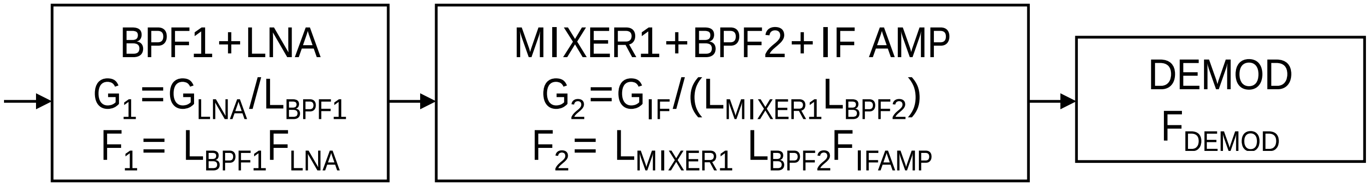
$$G_{receiver} = G_{LNA}\ G_{IF}\ /(L_{BPF1,}L_{MIXER1}L_{BPF2})$$

$$G_{receiver,\ dB} = -L_{BPF1,dB} + G_{LNA,dB} - L_{MIXER1,dB} - L_{BPF2,dB} + G_{IF,dB}$$

Overall noise factor (linear scale):

$$F_{receiver} = L_{BPF1} + (F_{LNA}-1)\ L_{BPF1} + (L_{MIXER1}-1)\ L_{BPF1}/G_{LNA} + (L_{BPF2}-1)\ L_{MIXER1}\ L_{BPF1}/G_{LNA} + (F_{IFAMP}-1)\ L_{MIXER1}\ L_{BPF1}\ L_{BPF2}/G_{LNA} + (F_{DEMOD}-1) L_{MIXER1}\ L_{BPF1}\ L_{BPF2}/G_{LNA}G_{IF}$$

OR EQUIVALENTLY, WE CAN GROUP VARIOUS BLOCKS AS FOLLOWS:



$$F_{receiver} = F_1 + (F_2-1)\ /G_1 + (F_{DEMOD}-1)/G_1G_2$$

equivalent noise temperature

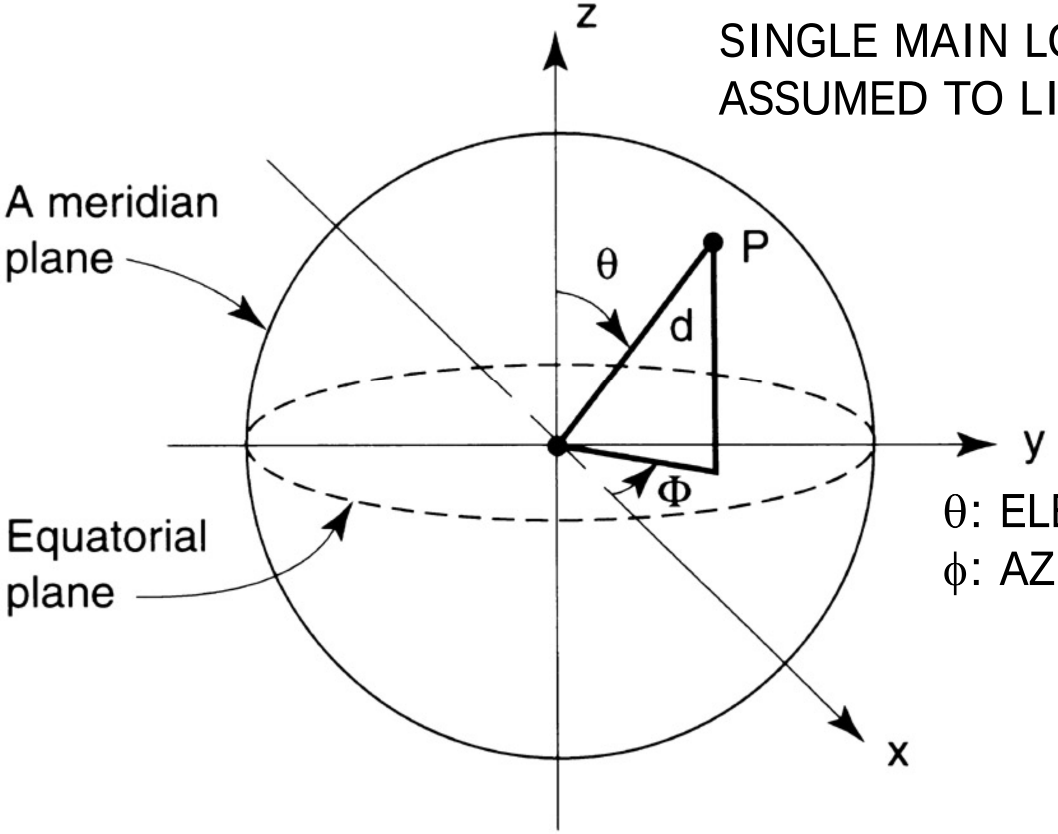
- For a receiver with an overall $F_{overall}$, $S_o/N_o=S_i/(N_i\,F_{overall})$ where $N_i=kT$ and T is the input absolute temperature.
- The effective noise spectral density at the receiver input is
  $N_i\,F_{overall}=kT\,F_{overall}$
- It can be expressed as:
  $N_i\,F_{overall}=kT+kT(F_{overall}-1)$
- Since the NF and F are specified at the reference temperature $T_o=290°K$, it is better to write
  $N_i\,F_{overall}=k(T+T_e)$ where T is the actual input temperature
  and $T_e=T_o(F_{overall}-1)$ is a hypothetical value equivalent to an excessive noise temperature due to the excessive noise spectral density generated by the system.
- In summary, the additional noise generated by the system or device can be expressed in terms of noise factor (F), noise figure (NF) and equivalent noise temperature (T_e) where $NF=10\log_{10}(F)$ and $T_e=T_o(F-1)$

SPHERICAL COORDINATES

θ: POLAR or COLATITUDE ANGLE

ϕ: LONGITUDE ANGLE

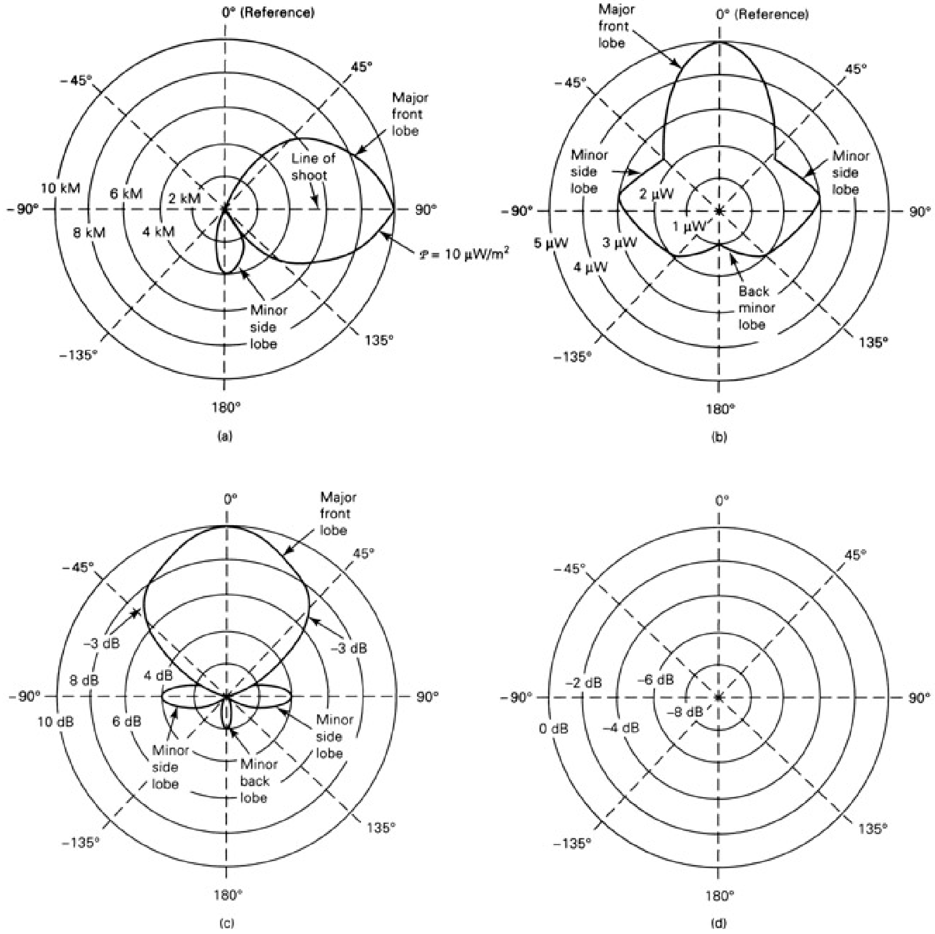
FOR CONVENIENCE, CONSIDER SINGLE MAIN LOBE WITH AXIS ASSUMED TO LIE IN THE xy-PLANE



θ: ELEVATION ANGLE

ϕ: AZIMUTH ANGLE

RADIATION PATTERNS



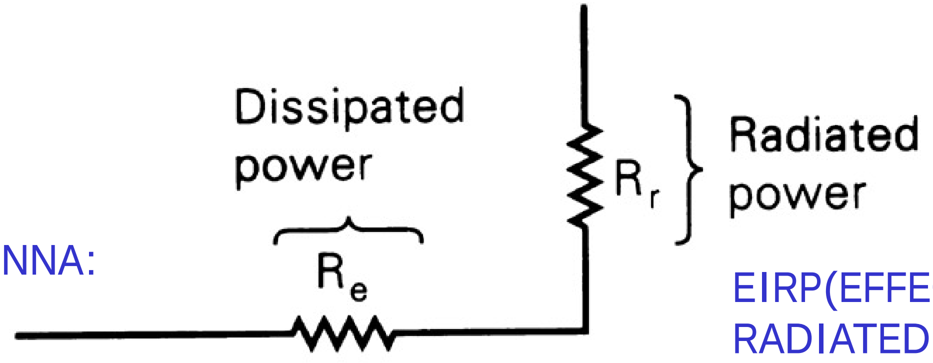
absolute (fixed power) radiation pattern

relative (fixed distance) radiation pattern

relative (fixed distance) radiation pattern in decibels

relative (fixed distance) radiation pattern in decibels for an omnidirectional (point source) antenna

SIMPLIFIED EQUIVALENT CIRCUIT OF AN ANTENNA



RF POWER TO ANTENNA:

$P_{RF(IN)}=P_D+P_R$

ANTENNA EFFICIENCY:

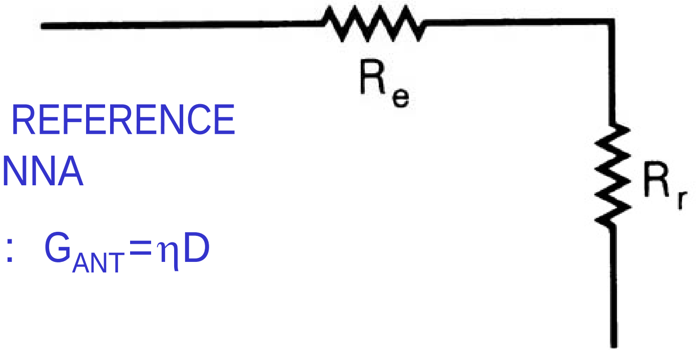
$\eta=P_R/P_{RF(IN)}=R_r/(R_r+R_e)$

ANT **DIRECTIVITY** GAIN:

$D=P/P_{REF}$,

P_{REF} : POWER OF A REFERENCE (ISOTROPIC) ANTENNA

ANT **POWER** GAIN: $G_{ANT}=\eta D$



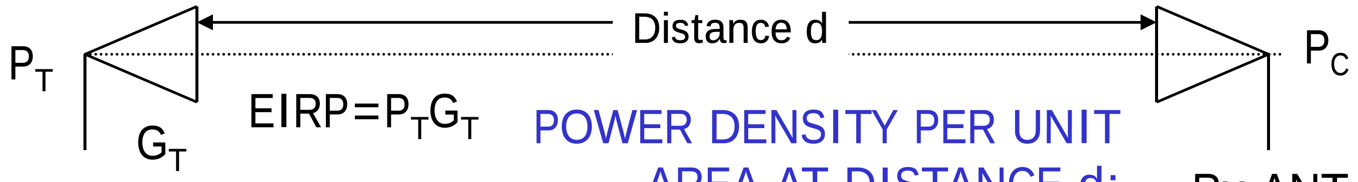
EIRP(EFFECTIVE ISOTROPIC RADIATED POWER)

$EIRP=P_R D=P_{RF(IN)}G_{ANT}$

POWER DENSITY PER UNIT AREA AT A POINT WITH DISTANCE d FROM ANT:

$p_d=(EIRP)/(4\pi d^2)$

CAPTURE AREA & CAPTURED POWER



POWER DENSITY PER UNIT
AREA AT DISTANCE d:
$p_d=(P_TG_T)/(4\pi d^2)$

Tx POWER P_T
Tx ANT POWER
GAIN G_T

Rx ANT POWER
GAIN G_R
Rx (CAPTURED)
POWER P_C

p_d : AMOUNT OF POWER INCIDENT ON EACH UNIT AREA OF AN IMAGINARY SURFACE (PERPENDICULAR TO THE DIRECTION OF PROPAGATION OF THE ELECTROMAGNETIC WAVE).

EFFECTIVE CAPTURE AREA OF THE Rx ANTENNA: $A_C=(G_R\lambda^2)/(4\pi)$

where $\lambda=c/f$: wavelength

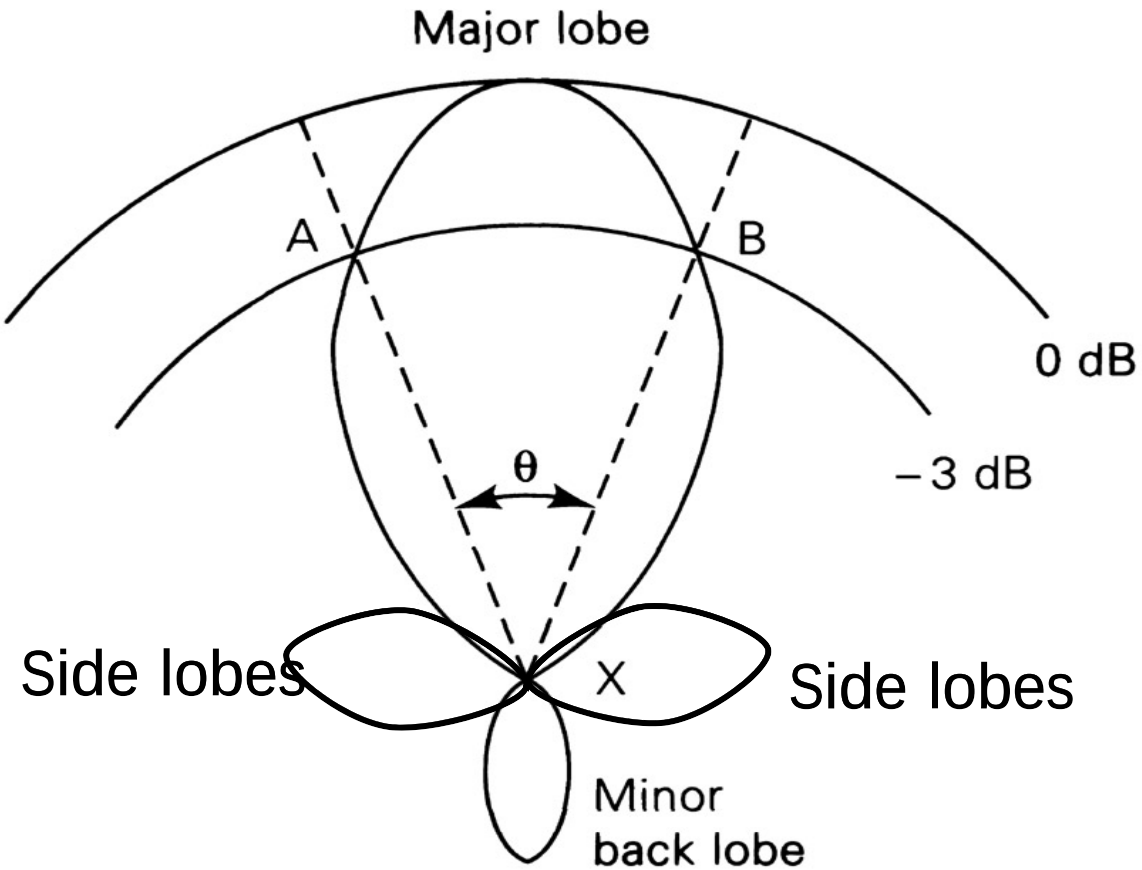
Rx CAPTURED POWER: $P_C=A_C\,p_C=(G_RP_TG_T\,\lambda^2)/(4\pi d)^2=P_T(G_TG_R)/(4\pi df/c)^2$

FREE-SPACE LOSS: $L_{FREE\text{-}SPACE}=(4\pi df/c)^2$

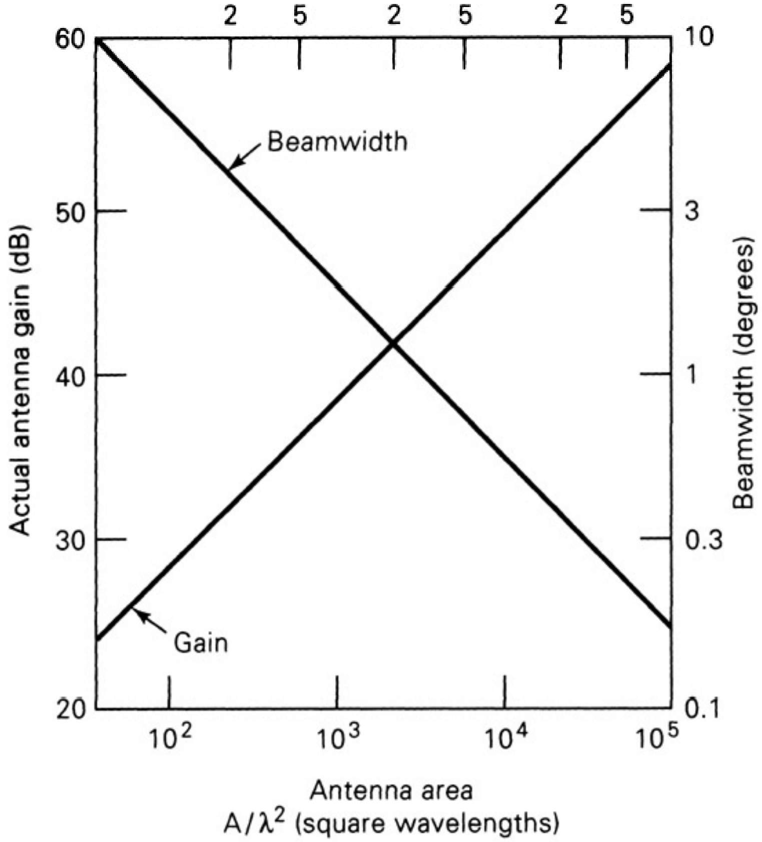
$$P_{C,dBm}=P_{T,dBm}+(G_{T,dB}+G_{R,dB})-L_{FS,\,dB}$$

$$L_{FS,\,dB}=10\log_{10}(L_{FREE\text{-}SPACE})=92.44+20\log_{10}(f_{GHz})+20\log_{10}(d_{km})$$

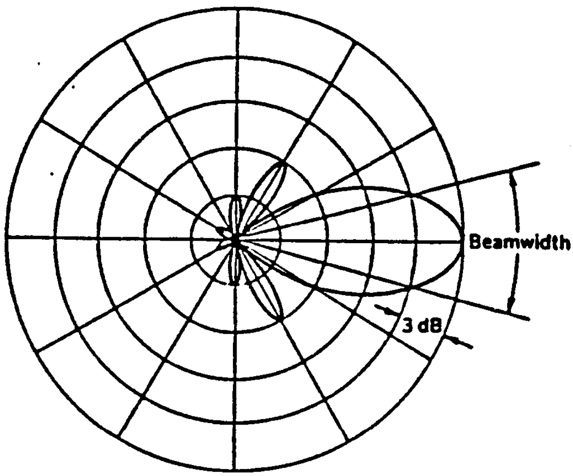
ANTENNA BEAMWIDTH



ANTENNA POWER GAIN AND BEAMWIDTH RELATIONSHIP



Note: Abscissa is actual antenna area, and actual antenna gain is taken to be 3 dB below theoretical.

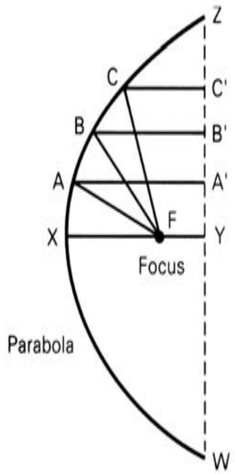


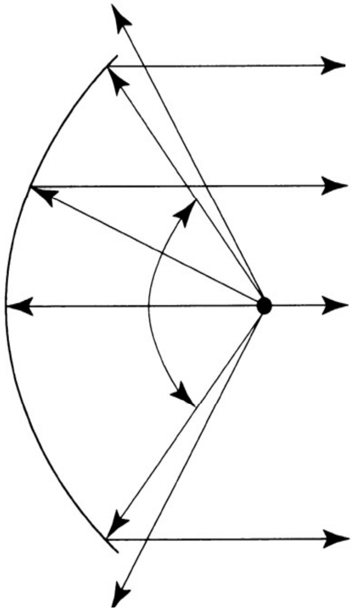
$$G = \frac{4\pi A}{\lambda^2}$$

$$\theta = \frac{142^\circ}{\sqrt{G}}$$

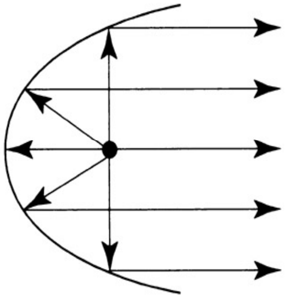
PARABOLIC REFLECTORS

GEOMETRY & RADIATION DIRECTIONS



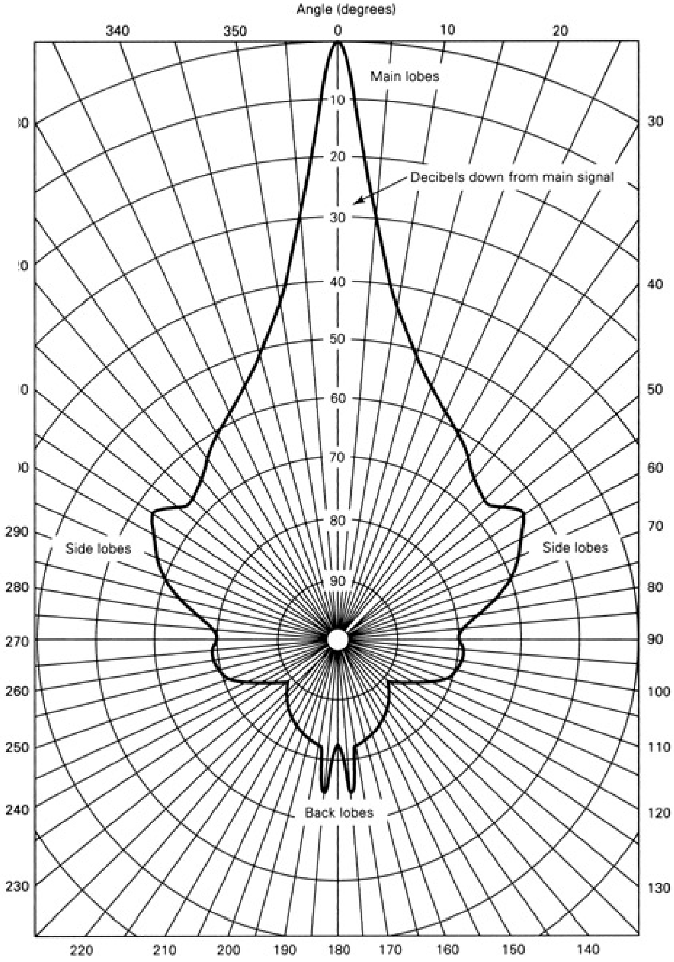


(a) focal point
outside the reflector

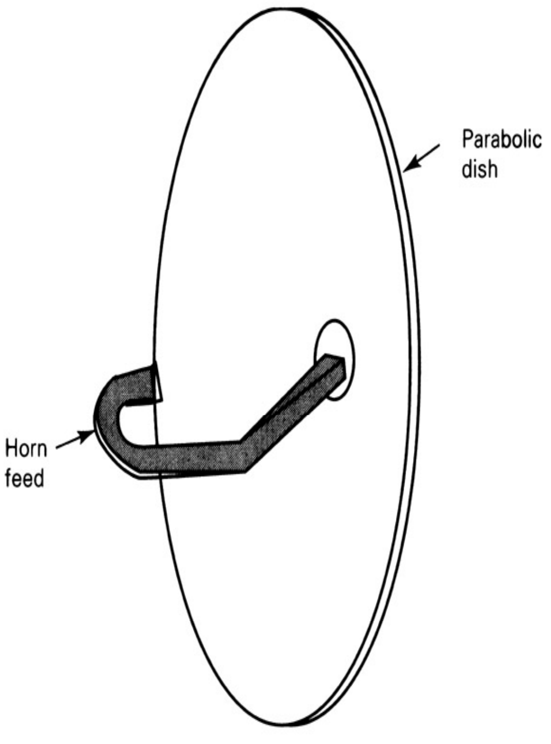


(b) focal point
inside the reflector

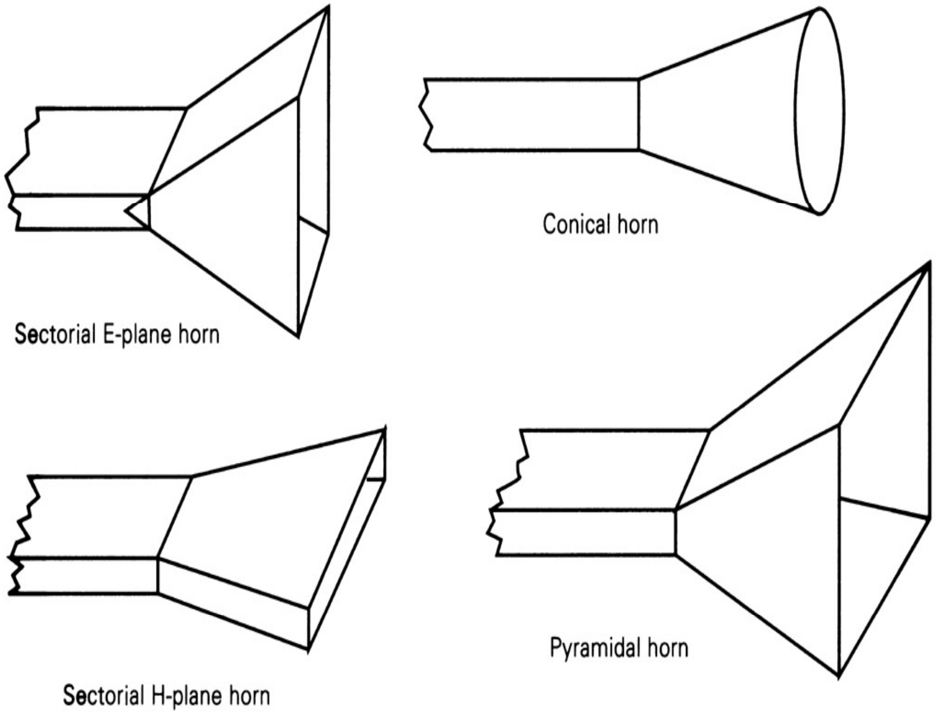
MAIN BEAM AND SIDE LOBES



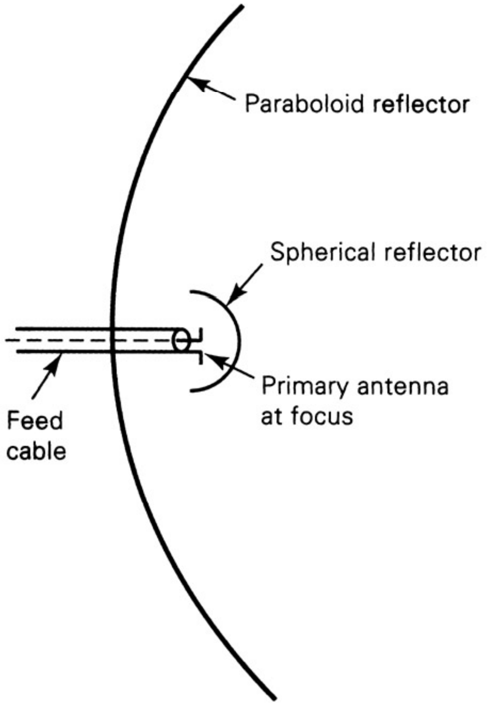
PARABOLIC ANTENNA WITH A HORN FEED: WAVEGUIDE HORN TYPES



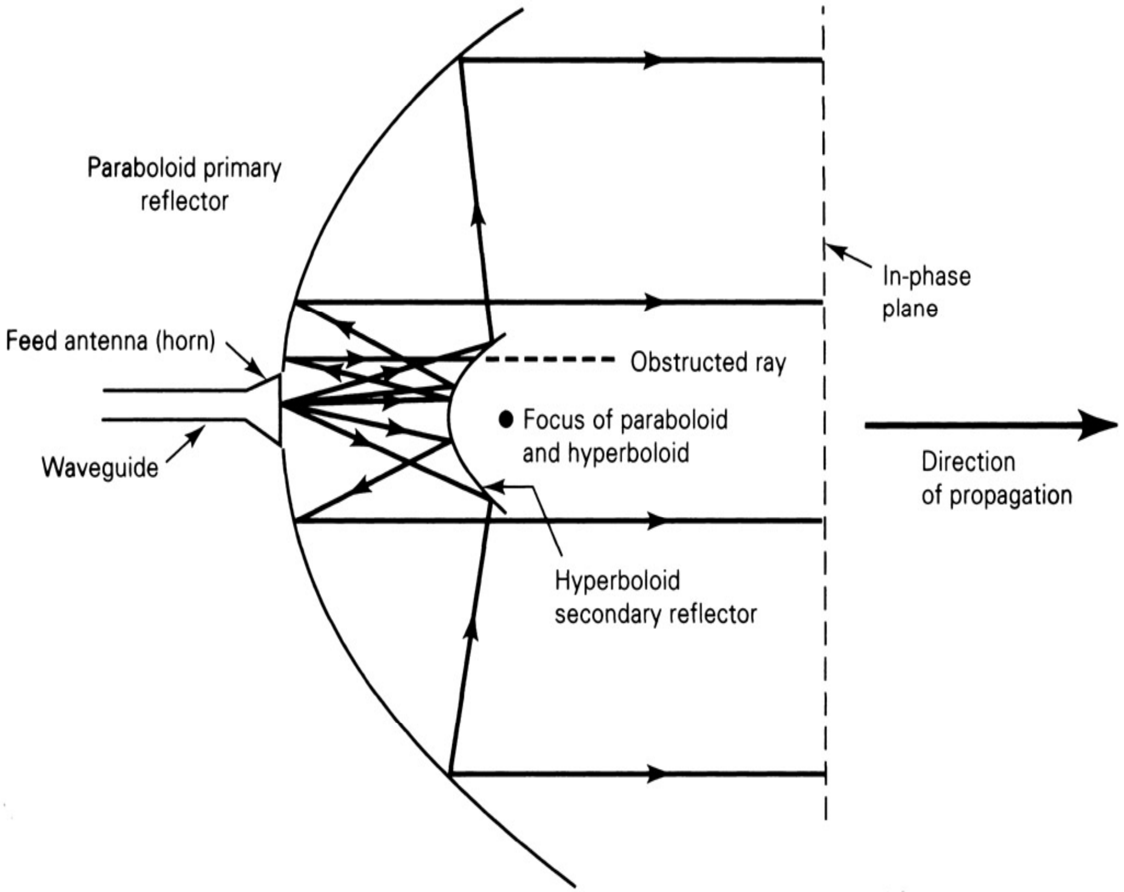
(a)



PARABOLIC ANTENNAS

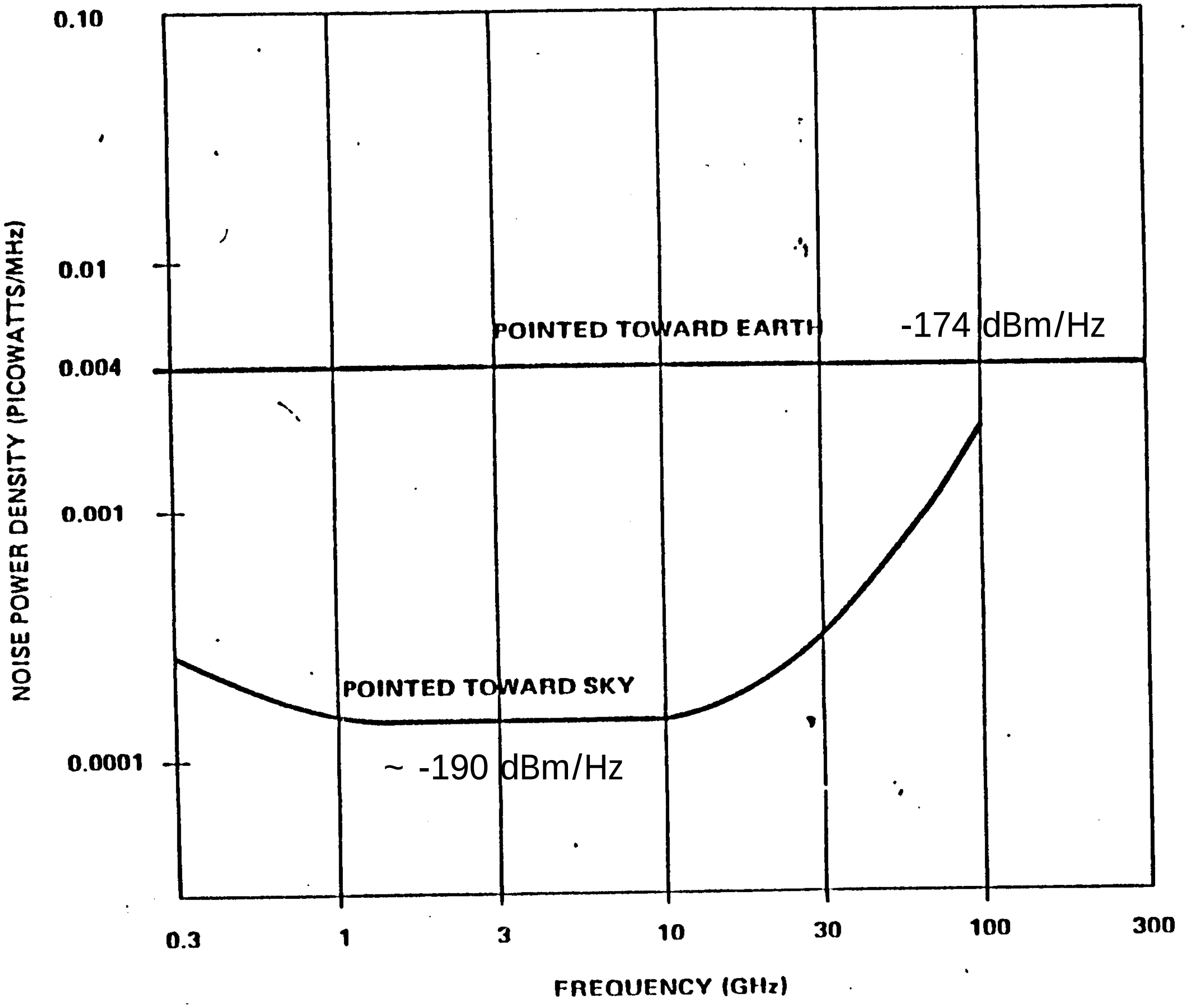


PARABOLIC ANTENNA WITH A CENTER FEED

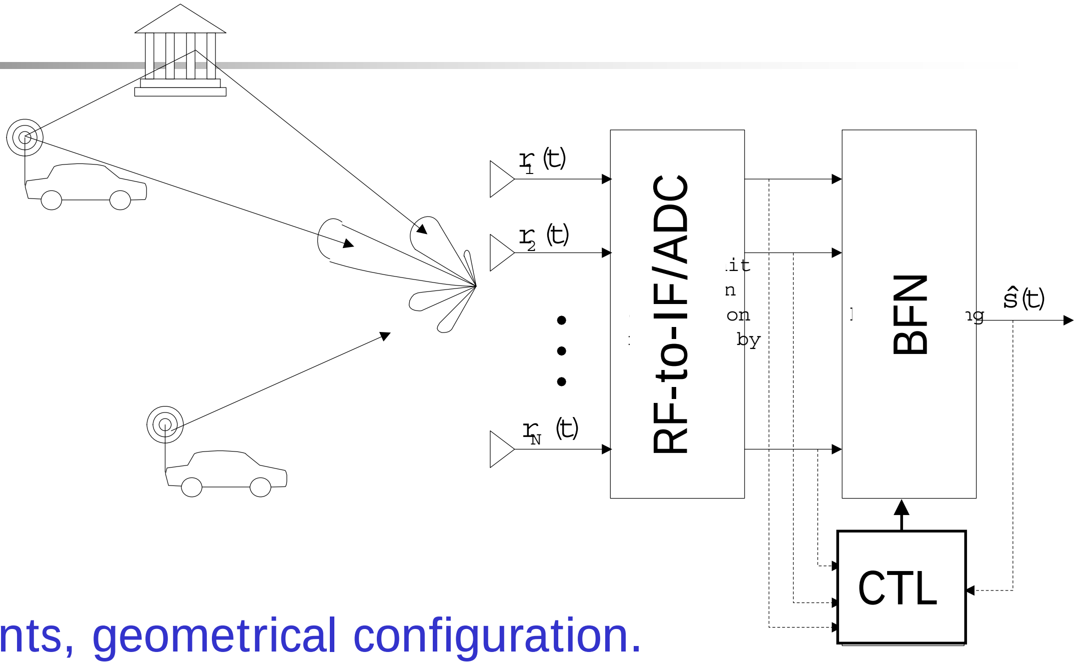


PARABOLIC ANTENNA WITH A CASSEGRAIN FEED

ANTENNA NOISE



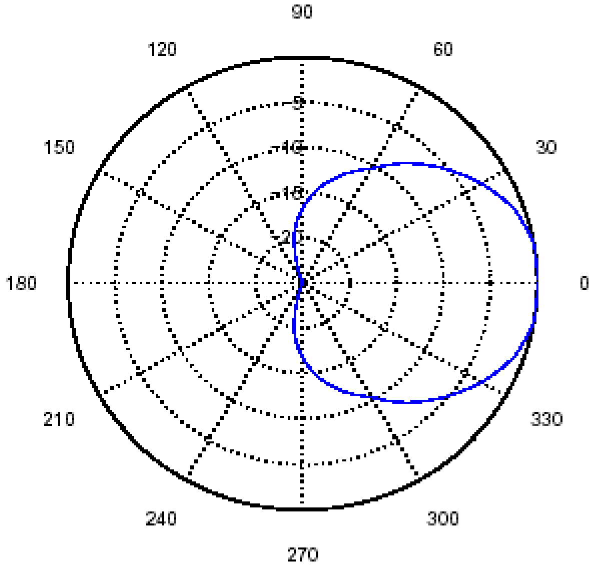
Smart Antenna Principles



- Smart antenna (SA) systems can be used for Rx and Tx.
- They exploit the spatial dimension via spatial sampling and coherent processing of the EM wave field.
- Four main system components (Rx mode):
  - Antenna array: N elements, geometrical configuration.
  - Radio unit: RF down-conversion, A/D conversion.
  - Beam-forming (BF) network (BFN): signal weighting followed by summation.
  - Control unit: adjusts BF weight to achieve desired spatial response.
- Ideally, a set of weights is maintained and updated for each individual mobile user.
- SA can adapt to current radio conditions and tailor individual user beam-patterns so as to maximize SIR:
  - Communication link continually optimized.

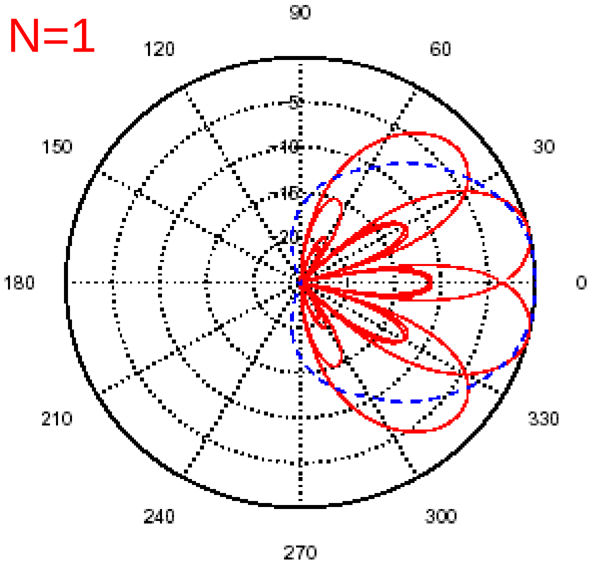
examples of antenna patterns

sector antenna

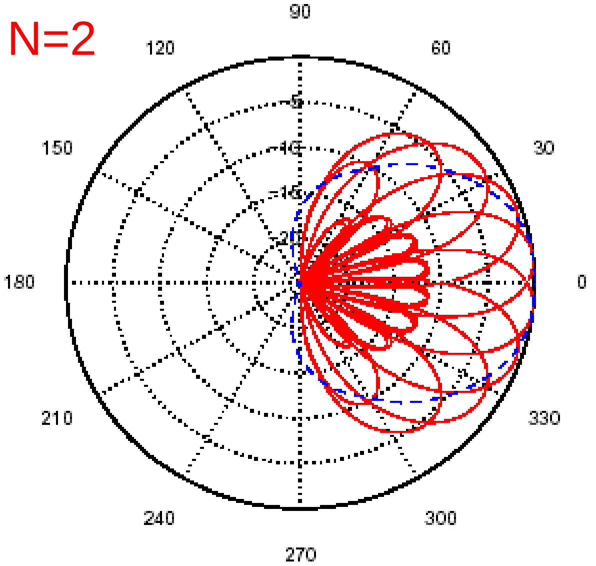


N sets of four orthogonal beams from a four-column antenna array with a 0.5λ horizontal element spacing

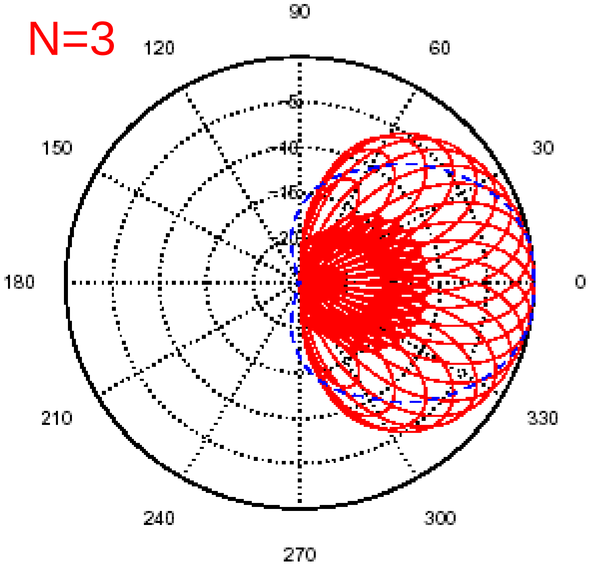
N=1



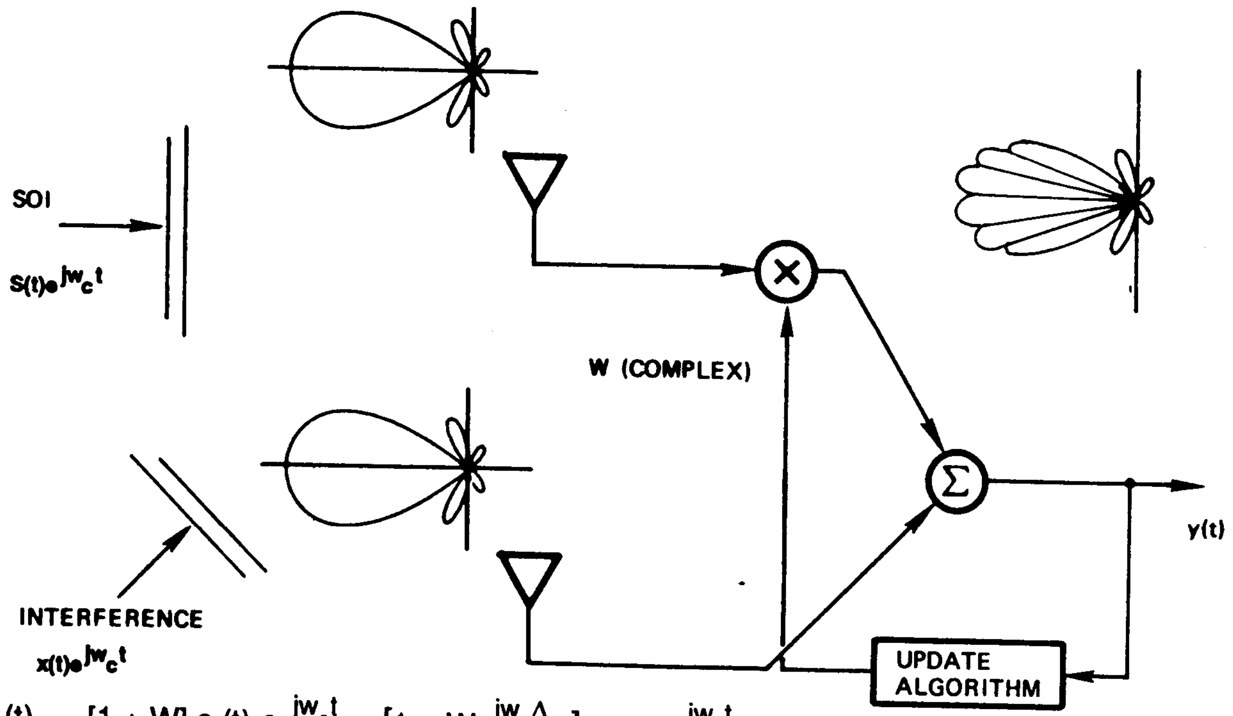
N=2



N=3



EXAMPLE OF BEAMFORMING TO IMPROVE SIR



$$y(t) = [1 + W]\, s(t)\, e^{jw_c t} + [1 + We^{jw_c \Delta}]\, x(t)\, e^{jw_c t}$$

assuming $x(t - \Delta) \approx x(t)$

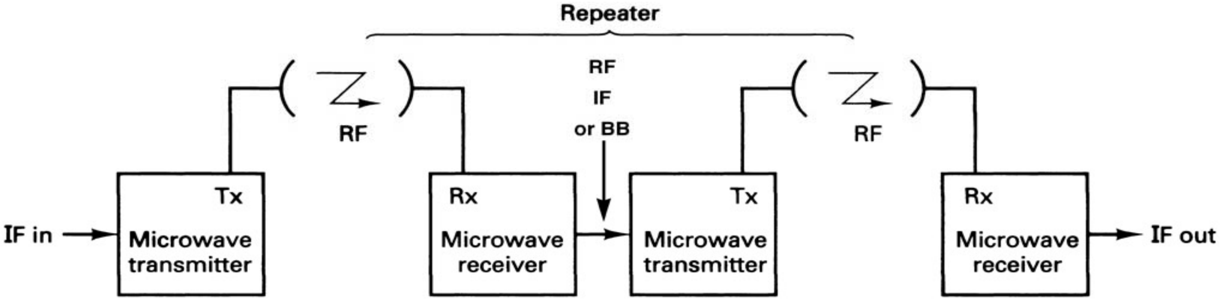
where Δ = propagation delay between antennas

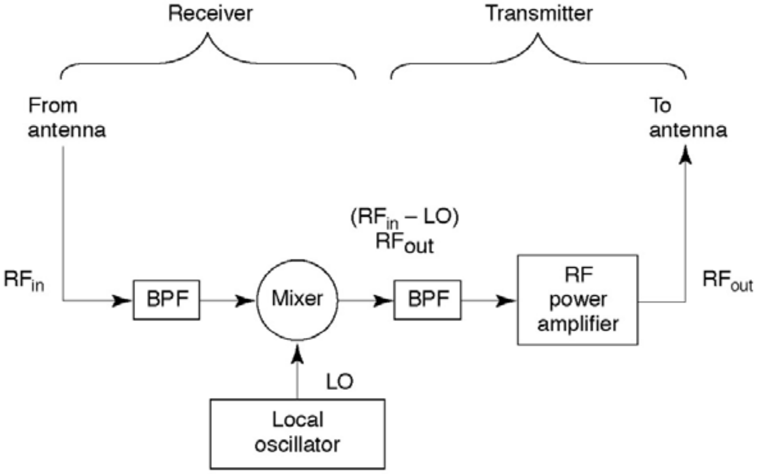
Choose W to maximize SINR $\approx \dfrac{1 + W}{1 + We^{jw_c \Delta}}$

Smart Antenna Classification

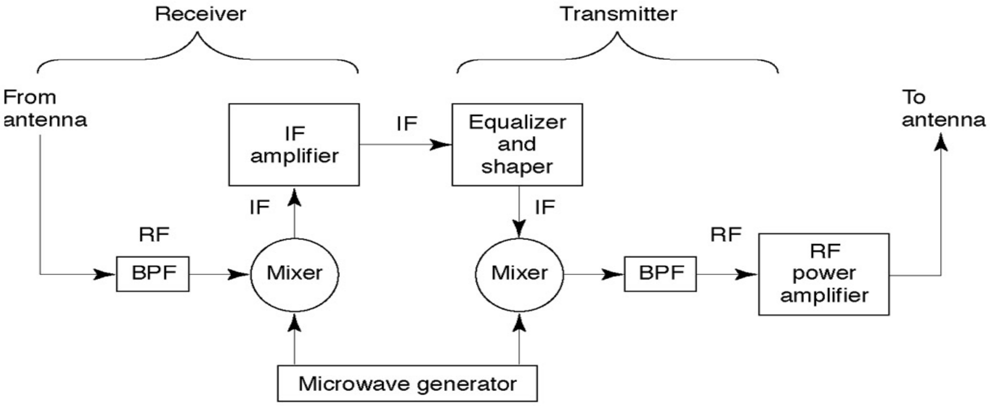
- Switched beam (SB) systems:
    - May be viewed as an extension to sectorization.
    - Uses fixed set of pre-computed beams.
    - Users assigned to different beams on the basis of received power.
    - Requires beam switching as users roam around.
- Dynamically phased array (DPA):
    - Ability to steer beams/nulls in arbitrary directions.
    - Requires angle of arrival (AOA) estimation of signal and possibly interference (several approaches available).
    - AOA info used to update BF weights so that SIR is maximized.
    - As users change location, AOA and BF weights continually updated.
- Adaptive antenna (AA) systems:
    - Uses fully adaptive scheme to optimize BF weights, based on available information: input/output signals, training sequence, etc.

Non-regenerative repeaters



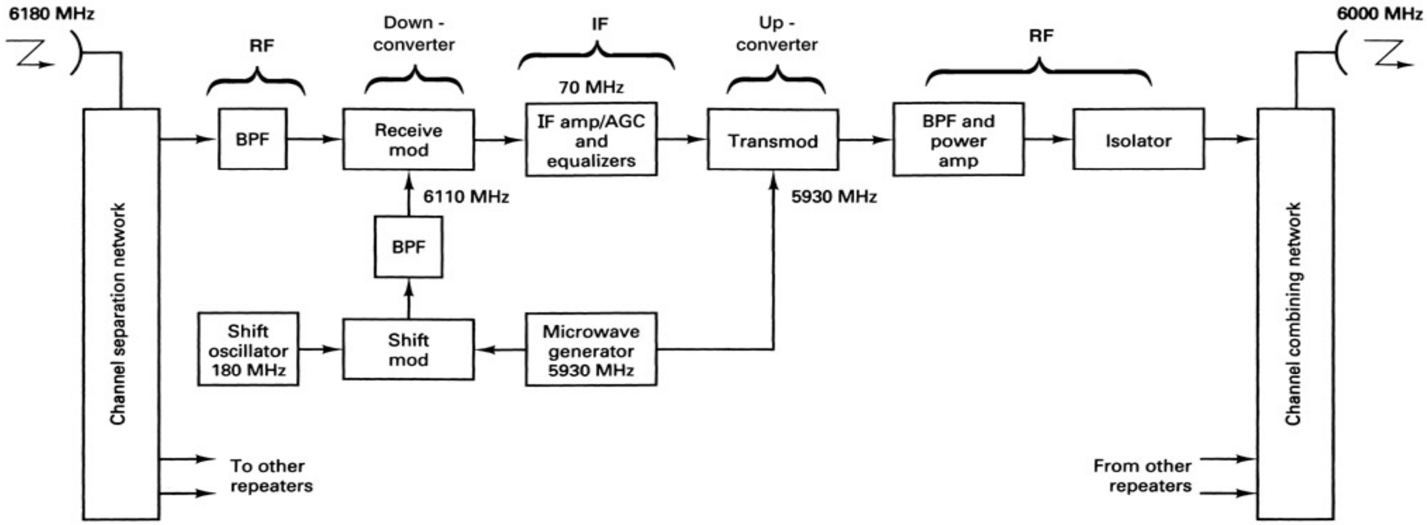


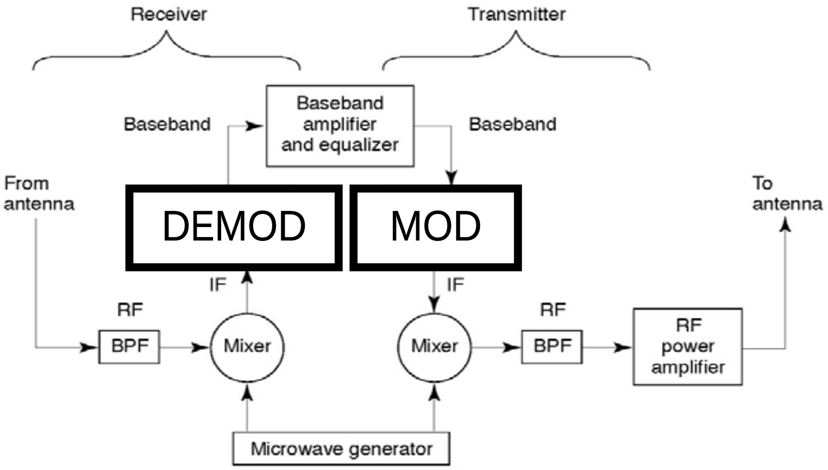
RF



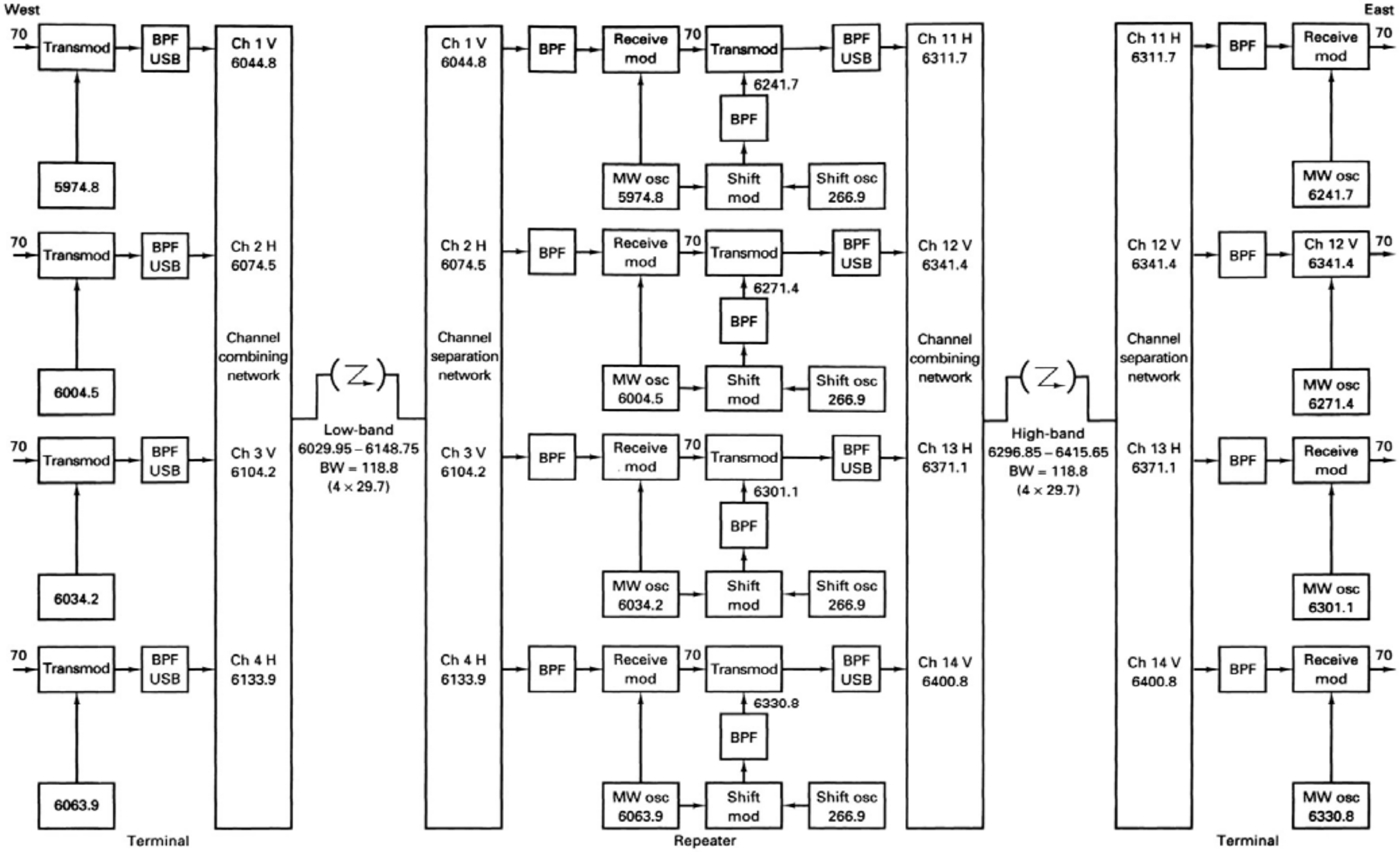
IF

BASEBAND REGENERATIVE REPEATER



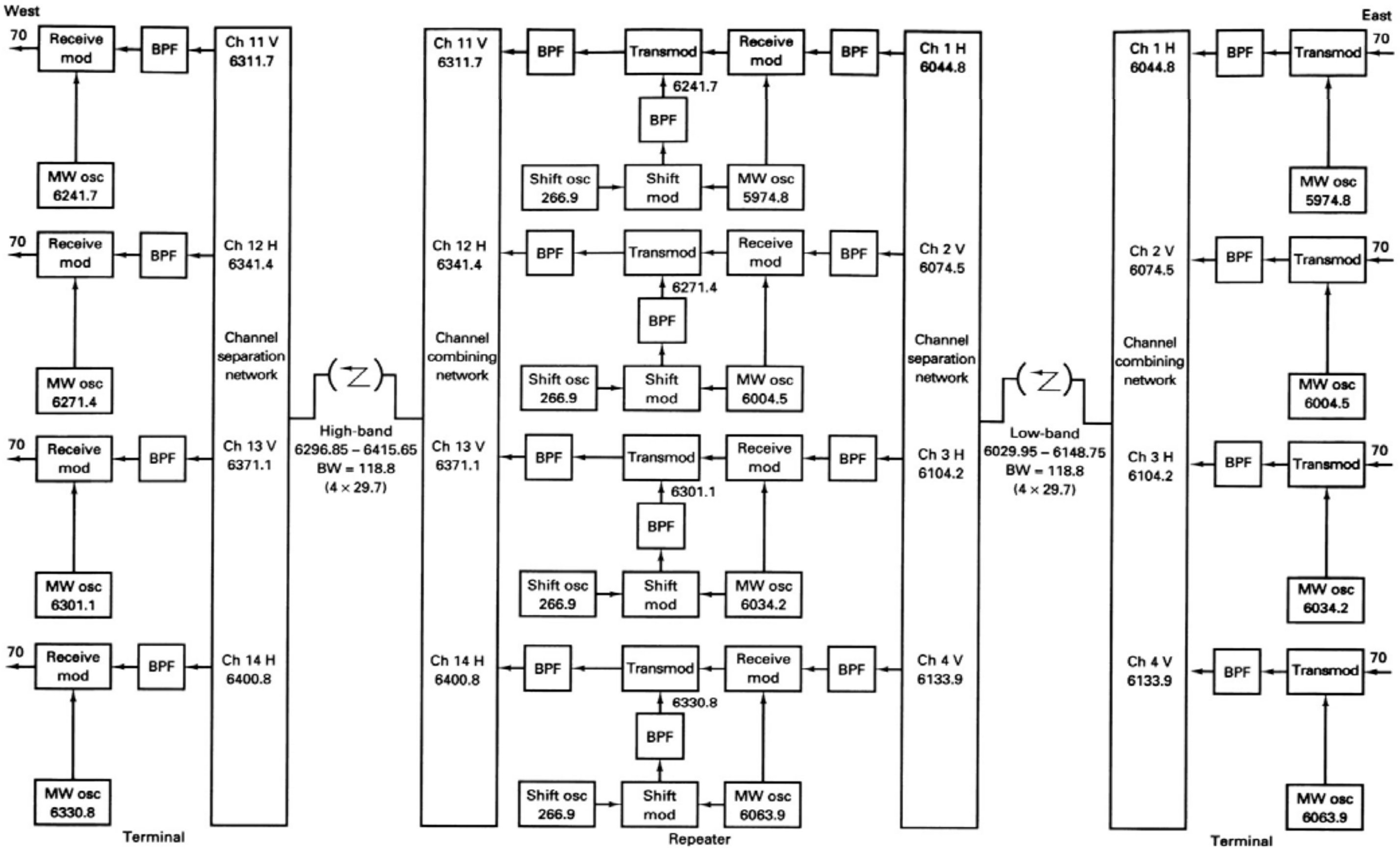


Example: 8-channel high / low frequency plan



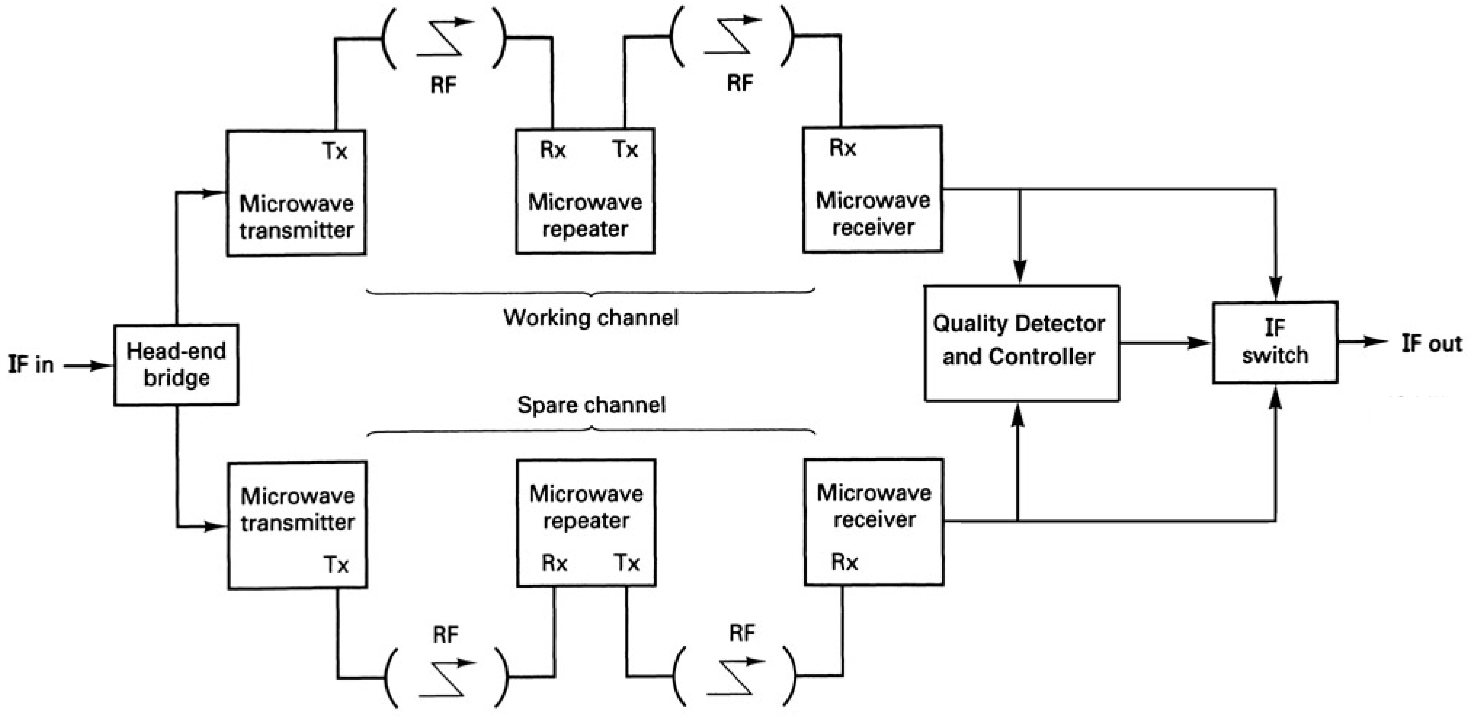
(a) west to east

Example: 8-channel high / low frequency plan

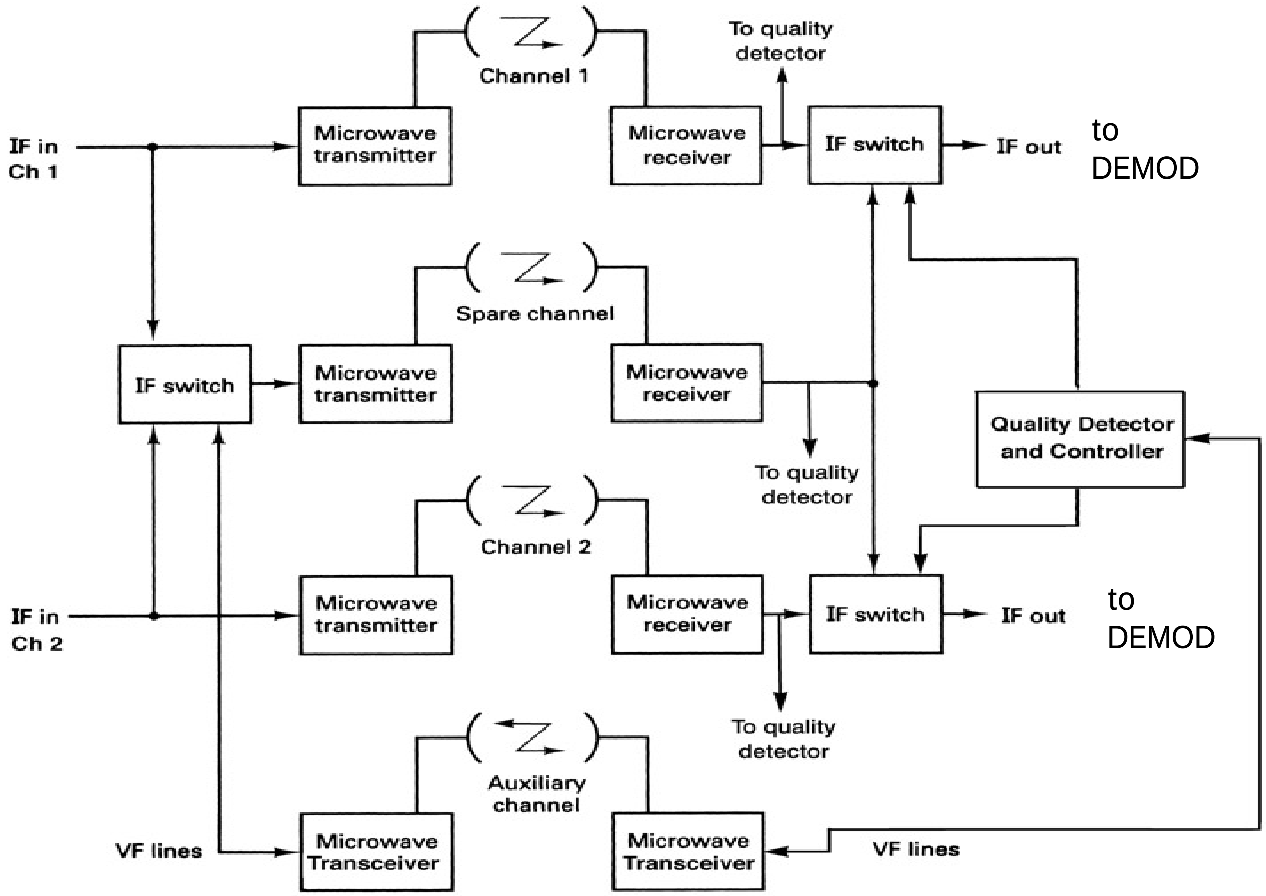


(b) east to west

protection switching arrangements: hot standby



protection switching arrangements: diversity



REFERENCES: materials from various sources