1

ELECTROMAGNETIC WAVE PROPAGATION AND APPLICATIONS

The purpose of this chapter is to provide a short survey of electromagnetic wave propagation and applications. The electromagnetic spectrum and basic definitions of electromagnetic wave propagation are presented in this chapter. Transmitting and receiving information in microwave frequencies are based on electromagnetic wave propagation.

1.1 ELECTROMAGNETIC SPECTRUM

The electromagnetic spectrum corresponds to electromagnetic waves from the meter range to the mm-wave range. The characteristic feature of this phenomenon is the short wavelength involved. The wavelength is of the same order of magnitude as the circuit devices used. The propagation time from one point of the circuit to another point of the circuit is comparable with period of the oscillating voltages and currents in the circuit. Conventional low circuit analysis based on Kirchhoff's and Ohm's laws could not analyze and describe the variation of fields, voltages, and currents along the length of the components. Components that their dimensions are lower than a 10th of wavelength are called lumped elements. Components that their dimensions are higher than a 10th of wavelength are called distributed elements. Kirchhoff's and Ohm's laws may be applied to lumped elements. However, Kirchhoff's and Ohm's laws cannot be applied to distributed elements.

Wideband RF Technologies and Antennas in Microwave Frequencies, First Edition. Dr. Albert Sabban.

TABLE 1.1 Electromagnetic Spectrum and Applications

Band Name	Abbreviation	ITU	Frequency\λ_0	Applications
Tremendously low frequency	TLF		<3 Hz >100,000 km	Natural and artificial EM noise
Extremely low frequency	ELF		3–30 Hz 100,000–10,000 km	Communication with submarines
Super low frequency	SLF		30–300 Hz 10,000–1000 km	Communication with submarines
Ultra low frequency	ULF		300–3000 Hz 1000–100 km	Submarine communication, communication within mines
Very low frequency	VLF	4	3–30 kHz 100–10 km	Navigation, time signals, submarine communication, wireless heart rate monitors, geophysics
Low frequency	LF	5	30–300 kHz 10–1 km	Navigation, clock time signals, AM longwave broadcasting (Europe and parts of Asia), RFID, amateur radio
Medium frequency	MF	6	300–3000 kHz 1–100 m	AM (medium-wave) broadcasts, amateur radio, avalanche beacons
High frequency	HF	7	3–30 MHz 100–10 m	Shortwave broadcasts, radio, amateur radio and aviation, communications, RFID, radar, near-vertical incidence skywave (NVIS) radio communications, marine and mobile radio telephony
Very high frequency	VHF	8	30–300 MHz 10–1 m	FM, television broadcasts and line-of-sight ground-to-aircraft and aircraft-to-aircraft communications, land mobile and maritime mobile communications, amateur radio, weather radio
Ultra high frequency	UHF	9	300–3000 MHz 1–100 mm	Television broadcasts, microwave oven, radio astronomy, mobile phones, wireless LAN, Bluetooth, ZigBee, GPS and two-way radios such as land mobile, FRS, and GMRS radios
Super high frequency	SHF	10	3–30 GHz 100–10 mm	Radio astronomy, wireless LAN, modern radars, communications satellites, satellite television broadcasting, DBS
Extremely high frequency	EHF	11	30–300 GHz 10–1 mm	Radio astronomy, microwave radio relay, microwave remote sensing, directed-energy weapon, scanners
Terahertz or tremendously high frequency	THz or THF	12	300–3000 GHz 1–100 μm	Terahertz imaging, ultrafast molecular dynamics, condensed-matter physics, terahertz time-domain spectroscopy, terahertz computing/communications

To prevent interference and to provide efficient use of the radio spectrum, similar services are allocated in bands (see Refs. [1–3]). Bands are divided at wavelengths of 10^n meters, or frequencies of 3×10^n Hz. Each of these bands has a basic band plan that dictates how it is to be used and shared to avoid interference and to set protocol for the compatibility of transmitters and receivers. In Table 1.1 the electromagnetic spectrum and applications are listed. In Table 1.2 the IEEE Standard for radar frequency bands is listed. In Table 1.3 the International Telecommunication Union (ITU) bands are given. In Table 1.4 radar frequency bands as defined by NATO for ECM systems are listed (see Ref. [4]).

TABLE 1.2 IEEE Standard Radar Frequency Bands

Microwave Frequency Bands—IEEE Standard

Designation	Frequency Range (GHz)
L band	1–2
S band	2–4
C band	4–8
X band	8–12
K_u band	12–18
K band	18–26.5
K_a band	26.5–40
Q band	30–50
U band	40–60
V band	50–75
E band	60–90
W band	75–110
F band	90–140
D band	110–170

TABLE 1.3 The International Telecommunication Union Bands

Band Number	Symbols	Frequency Range	Wavelength Range
4	VLF	3–30 kHz	10–100 km
5	LF	30–300 kHz	1–10 km
6	MF	300–3000 kHz	100–1000 m
7	HF	3–30 MHz	10–100 m
8	VHF	30–300 MHz	1–10 m
9	UHF	300–3000 MHz	10–100 cm
10	SHF	3–30 GHz	1–10 cm
11	EHF	30–300 GHz	1–10 mm
12	THF	300–3000 GHz	0.1–1 mm

TABLE 1.4 Radar Frequency Bands as Defined by NATO for ECM Systems[a]

Band	Frequency Range (GHz)
A band	0–0.25
B band	0.25–0.5
C band	0.5–1.0
D band	1–2
E band	2–3
F band	3–4
G band	4–6
H band	6–8
I band	8–10
J band	10–20
K band	20–40
L band	40–60
M band	60–100

[a] Ref. [4].

1.2 FREE-SPACE PROPAGATION

Consider an isotropic source radiating P_t watts uniformly into free space.

At distance R, the area of the spherical shell with center at the source is $4\pi R^2$.

Flux density at distance R is given by Equation 1.1:

$$F = \frac{P_t}{4\pi R^2}\ \mathrm{W/m^2} \tag{1.1}$$

$$G(\theta) = \frac{P(\theta)}{P_0/4\pi} \tag{1.2}$$

where

$P(\theta)$ is the variation of power with angle
$G(\theta)$ is the gain at the direction θ
P_0 is the total power transmitted
Sphere = 4π solid radians

Gain is usually expressed in **decibels** (dB): $G\,[\mathrm{dB}] = 10\log_{10} G$. Gain is realized by focusing power. An isotropic radiator is an antenna that radiates in all directions equally. Effective isotropic radiated power (EIRP) is the amount of power the transmitter would have to produce if it was radiating to all directions equally. The EIRP may vary as a function of direction because of changes in the antenna gain versus angle. We now want to find the power density at the receiver. We know that power is conserved in a lossless medium. The power radiated from a transmitter must pass through a spherical shell on the surface of which is the receiver.

The area of this spherical shell is $4\pi R^2$.

Therefore spherical spreading loss is $1/4\pi R^2$.

We can rewrite the power flux density, as given in Equation 1.3, now considering the transmit antenna gain:

$$F = \frac{\text{EIRP}}{4\pi R^2} = \frac{P_\text{t} G_\text{t}}{4\pi R^2}\ \text{W/m}^2 \tag{1.3}$$

The power available to a receive antenna of area A_r is given in Equation 1.4:

$$P_\text{r} = F \times A_\text{r} = \frac{P_\text{t} G_\text{t} A_\text{r}}{4\pi R^2} \tag{1.4}$$

Real antennas have effective flux collecting areas, which are less than the physical aperture area. A_e is defined as the antenna effective aperture area.

Where $A_\text{e} = A_\text{phy} \times \eta$, $\eta =$ aperture efficiency.

Antennas have maximum gain G related to the effective aperture area as f as given in Equation 1.5, where A_e is the effective aperture area:

$$G = \text{Gain} = \frac{4\pi A_\text{e}}{\lambda^2} \tag{1.5}$$

Aperture antennas (horns and reflectors) have a physical collecting area that can be easily calculated from their dimensions:

$$A_\text{phy} = \pi r^2 = \pi \frac{D^2}{4} \tag{1.6}$$

Therefore, using Equations 1.5 and 1.6 we can obtain the formula for aperture antenna gain as given in Equations 1.7 and 1.8:

$$\text{Gain} = \frac{4\pi A_\text{e}}{\lambda^2} = \frac{4\pi A_\text{phy}}{\lambda^2} \times \eta \tag{1.7}$$

$$\text{Gain} = \left(\frac{\pi D}{\lambda}\right)^2 \times \eta \tag{1.8}$$

$$\text{Gain} \cong \eta \left(\frac{75\pi}{\theta_\text{3dB}}\right)^2 = \eta \frac{(75\pi)^2}{\theta_{\text{3dB}H}\theta_{\text{3dB}E}} \tag{1.9}$$

$$\text{where } \theta_\text{3dB} \cong \frac{75\lambda}{D}$$

θ_3dB is the antenna half power beamwidth. Assuming, for instance, a typical aperture efficiency of 0.55 gives

$$\text{Gain} \cong \frac{30{,}000}{(\theta_\text{3dB})^2} = \frac{30{,}000}{\theta_{\text{3dB}H}\theta_{\text{3dB}E}} \tag{1.10}$$

1.3 FRIIS TRANSMISSION FORMULA

The Friis transmission formula is presented in Equation 1.11:

$$P_{\mathrm{r}} = P_{\mathrm{t}} G_{\mathrm{t}} G_{\mathrm{r}} \left(\frac{\lambda}{4\pi R} \right)^2 \tag{1.11}$$

Free-space loss (L_{p}) represents propagation loss in free space (e.g., losses due to attenuation in atmosphere)

where $L_{\mathrm{p}} = (4\pi R/\lambda)^2$. The received power may be given as $P_{\mathrm{r}} = \left(P_{\mathrm{t}} G_{\mathrm{t}} G_{\mathrm{r}}/L_{\mathrm{p}}\right)$.

L_{a} should also be accounted for in the transmission equation. Losses due to polarization mismatch, L_{pol}, should also be accounted. Losses associated with receiving antenna, L_{ra}, and with the receiver, L_{r}, cannot be neglected in computation of transmission budget. Losses associated with the transmitting antenna can be written as L_{ta}:

$$P_{\mathrm{r}} = \frac{P_{\mathrm{t}} G_{\mathrm{t}} G_{\mathrm{r}}}{L_{\mathrm{p}} L_{\mathrm{a}} L_{\mathrm{ta}} L_{\mathrm{ra}} L_{\mathrm{pol}} L_{\mathrm{o}} L_{\mathrm{r}}} \tag{1.12}$$

$$P_{\mathrm{t}} = \frac{P_{\mathrm{out}}}{L_{\mathrm{t}}}$$

$$\mathrm{EIRP} = P_{\mathrm{t}} G_{\mathrm{t}}$$

where

P_{t} is the transmitting antenna power

L_{t} is the loss between power source and antenna

EIRP is the effective isotropic radiated power

$$\begin{aligned} P_{\mathrm{r}} &= \frac{P_{\mathrm{t}} G_{\mathrm{t}} G_{\mathrm{r}}}{L_{\mathrm{p}} L_{\mathrm{a}} L_{\mathrm{ta}} L_{\mathrm{ra}} L_{\mathrm{pol}} L_{\mathrm{other}} L_{\mathrm{r}}} \\ &= \frac{\mathrm{EIRP} \times G_{\mathrm{r}}}{L_{\mathrm{p}} L_{\mathrm{a}} L_{\mathrm{ta}} L_{\mathrm{ra}} L_{\mathrm{pol}} L_{\mathrm{other}} L_{\mathrm{r}}} \\ &= \frac{P_{\mathrm{out}} G_{\mathrm{t}} G_{\mathrm{r}}}{L_{\mathrm{t}} L_{\mathrm{p}} L_{\mathrm{a}} L_{\mathrm{ta}} L_{\mathrm{ra}} L_{\mathrm{pol}} L_{\mathrm{other}} L_{\mathrm{r}}} \end{aligned} \tag{1.13}$$

where

$$G = 10\log\left(\frac{P_{\mathrm{out}}}{P_{\mathrm{in}}}\right) \mathrm{dB} \quad \text{gain in dB}$$

$$L = 10\log\left(\frac{P_{\mathrm{in}}}{P_{\mathrm{out}}}\right) \mathrm{dB} \quad \text{loss in dB}$$

Gain may be derived as given in Equation 1.14:

$$\begin{aligned}
&P_{\text{in}} = \frac{V_{\text{in}}^2}{R_{\text{in}}} \qquad P_{\text{out}} = \frac{V_{\text{out}}^2}{R_{\text{out}}} \\
&G = 10\log\left(\frac{P_{\text{out}}}{P_{\text{in}}}\right) = 10\log\left(\frac{V_{\text{out}}^2/R_{\text{out}}}{V_{\text{in}}^2/R_{\text{in}}}\right) \\
&G = 10\log\left(\frac{V_{\text{out}}^2}{V_{\text{in}}^2}\right) + 10\log\left(\frac{R_{\text{in}}}{R_{\text{out}}}\right) = 20\log\left(\frac{V_{\text{out}}}{V_{\text{in}}}\right) + 10\log\left(\frac{R_{\text{in}}}{R_{\text{out}}}\right)
\end{aligned} \tag{1.14}$$

1.3.1 Logarithmic Relations

Important logarithmic operations are listed in Equations 1.15–1.18:

$$\begin{aligned}
&10\log_{10}(A \times B) \\
&\quad = 10\log_{10}(A) + 10\log_{10}(B) \\
&\quad = A \text{ dB} + B \text{ dB} \\
&\quad = (A + B) \text{ dB}
\end{aligned} \tag{1.15}$$

$$\begin{aligned}
&10\log_{10}(A/B) \\
&\quad = 10\log_{10}(A) - 10\log_{10}(B) \\
&\quad = A \text{ dB} - B \text{ dB} \\
&\quad = (A - B) \text{ dB}
\end{aligned} \tag{1.16}$$

$$\begin{aligned}
&10\log_{10}(A^2) \\
&\quad = 2 \times 10\log_{10}(A) \\
&\quad = 20\log_{10}(A) \\
&\quad = 2 \times (A \text{ in dB})
\end{aligned} \tag{1.17}$$

$$\begin{aligned}
&10\log_{10}\left(\sqrt{A}\right) \\
&\quad = \frac{10}{2}\log_{10}(A) \\
&\quad = \frac{1}{2} \times (A \text{ in dB})
\end{aligned} \tag{1.18}$$

In Table 1.5 linear ratio versus logarithmic ratio is listed.

The received power P_r in dBm is given in Equation 1.19. The received power P_r is commonly referred to as “carrier power,” C:

$$P_r = \text{EIRP} - L_{\text{ta}} - L_{\text{p}} - L_{\text{a}} - L_{\text{pol}} - L_{\text{ra}} - L_{\text{other}} + G_r - L_r \tag{1.19}$$

TABLE 1.5 Linear Ratio versus Logarithmic Ratio

Linear Ratio	dB	Linear Ratio	dB
0.001	−30.0	2.000	3.0
0.010	−20.0	3.000	4.8
0.100	−10.0	4.000	6.0
0.200	−7.0	5.000	7.0
0.300	−5.2	6.000	7.8
0.400	−4.0	7.000	8.5
0.500	−3.0	8.000	9.0
0.600	−2.2	9.000	9.5
0.700	−1.5	10.000	10.0
0.800	−1.0	100.000	20.0
0.900	−0.5	1000.000	30.0
1.000	0.0	18.000	12.6

The surface area of a sphere of radius d is $4\pi d^2$, so that the power flow per unit area W (power flux in W/m^2) at distance d from a transmitter antenna with input power P_T and antenna gain G_T is given in Equation 1.20:

$$W = \frac{P_r G_r}{4\pi d^2} \tag{1.20}$$

The received signal strength depends on the “size” or aperture of the receiving antenna. If the antenna has an effective area A, then the received signal strength is given in Equation 1.21:

$$P_R = P_T G_T \left(\frac{A}{4\pi d^2}\right) \tag{1.21}$$

Define the receiver antenna gain $G_R = 4\pi A/\lambda^2$
where $\lambda = c/f$.

1.4 LINK BUDGET EXAMPLES

$F = 2.4$ GHz => $\lambda = 12.5$ cm
At 933 MHz => $\lambda = 32$ cm.
Receiver signal strength: $P_R = P_T\ G_T\ G_R\ (\lambda/4\pi d)^2$
P_R (dBm) = P_T (dBm) + G_T (dBi) + G_R (dBi) + $10\log_{10}((\lambda/4\pi)^2) - 10\log_{10}(d^2)$
For $F = 2.4$ GHz => $10\log_{10}((\lambda/4\pi)^2) = -40$dB
For $F = 933$ MHz => $10\log_{10}((\lambda/4\pi)^2) = -32$dB

Mobile phone downlink

$\lambda = 12.5$ cm

$f = 2.4$ GHz

P_R (dBm) $= (P_T\ G_T\ G_R L)$ (dBm) $-$ 40dB $+ 10\log_{10}(1/d^2)$

$P_R - (P_T + G_T + G_R + L) -$ 40dB $= 10\log_{10}(1/d^2)$

Or $155 - 40 = 10\log_{10}(1/d^2)$

Or $(155 - 40)/20 = \log_{10}(1/d)$

$d = 10$^ $((155 - 40)/20) = 562$ km

Mobile phone uplink

$d = 10$^ $((153 - 40)/20) = 446$ km

For standard 802.11

- $P_R - P_T = -113.2$dBm
- 6 Mbps
    - $d = 10^{(113.2-40)/20} = 4500$ m
    - $d = 10^{(113.2-40-3)/20} = 3235$ m with 3dB gain margin
    - $d = 10^{(113.2-40-3-9)/20} = 1148$ m with 3dB gain margin and neglecting antenna gains
- 54 Mbps needing −85dBm
    - $d = 10^{(99.2-40)/20} = 912$ m
    - $d = 10^{(99.2-40-3)/20} = 646$ m with 3dB gain margin
    - $d = 10^{(99.2-40-3-9)/20} = 230$ m with 3dB gain margin and neglecting antenna gains

Signal strength

Measure signal strength in

dBW = 10log (power in watts)

dBm = 10log (power in mW)

802.11 can legally transmit at 30dBm.

Most 802.11 PCMCIA cards transmit at 10–20dBm.

Mobile phone base station: 20 W, but 60 users, so 0.3 W/user, but antenna has gain = 18dBi.

Mobile phone handset: 21dBm

1.5 NOISE

Noise limits systems ability to process weak signals.

System dynamic range is defined as system capability to detect weak signals in presence of large-amplitude signals.

Noise sources

1. Random noise in resistors and transistors
2. Mixer noise
3. Undesired cross-coupling noise from other transmitters and equipment
4. Power supply noise
5. Thermal noise present in all electronics and transmission media due to thermal agitation of electrons

$$\text{Thermal noise} = kTB \text{ (W)}$$

where k is Boltzmann's constant = 1.38 × 10^−23
T is temperature in Kelvin (C + 273)
B is bandwidth

Examples

For temperature = 293°C= > −203dB, −173dBm/Hz
For temperature = 293°C and 22 MHz = > −130dB, −100dBm

Random noise

- External noise
- Atmospheric noise
- Interstellar noise

Receiver internal

- Thermal noise
- Flicker noise (low frequency)
- Shot noise

SNR is defined as signal-to-noise ratio. SNR varies with frequency.
SNR = signal power/noise power, and SNR is given in Equation 1.22:

$$\text{SNR} = \frac{S(f)}{N(f)} = \frac{\text{average signal power}}{\text{average noise power}} \tag{1.22}$$

- SNR (dB) = $10\log_{10}$ (signal power/noise power).

Noise factor, F, is a measure of the degradation of SNR due to the noise added as we process the signal. F is given in Equations 1.23 and 1.24:

$$F = \frac{\text{available output noise power}}{\text{available output noise due to source}} \tag{1.23}$$

$$\text{Noise figure} = \text{NF} = 10\log(F).$$

Multistage noise figure is given by Equation 1.24:

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots + \frac{F_n - 1}{G_1 G_2 \cdots G_{n-1}} \tag{1.24}$$

Signal strength is the transmitted power multiplied by a gain minus losses.

Loss sources

- Distance between the transmitter and the receiver.
- The signal passes through rain or fog at high frequencies.
- The signal passes through an object.
- Part of the signal is reflected from an object.
- Signal interferes multipath fading.
- An object not directly in the way impairs the transmission.

The received signal must have a strength that is larger than the receiver sensitivity. SNR of 20dB or larger would be good.

Sensitivity is defined as minimum detectable input signal level for a given output SNR, also called noise floor.

1.6 COMMUNICATION SYSTEM LINK BUDGET

Link budget determines if the received signal is larger than the receiver sensitivity.

A link budget analysis determines if there is enough power at the receiver to recover the information. Link budget must account for effective transmission power. Link budget takes into account the following parameters:

Transmitter

- Transmission power
- Antenna gain
- Losses in cable and connectors

Path losses

- Attenuation
- Ground reflection
- Fading (self-interference)

Receiver

- Receiver sensitivity
- Losses in cable and connectors

1.6.1 Transmitter

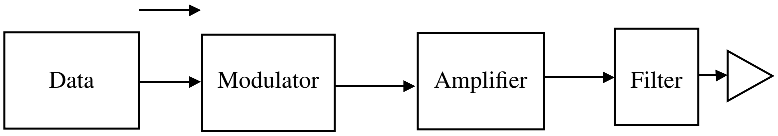

FIGURE 1.1 Transmitter block diagram.

1.6.2 Receiver

Transmitter block diagram is shown in Figure 1.1 (Table 1.6). Receiver block diagram is shown in Figure 1.2 (Table 1.7).

TABLE 1.6 Transmitting Channel Power Budget

Component	Gain (dB)/Loss (dB)	Power (dBm)	Remarks
Input power		–2	
Transmitter gain	40		
Power amplifier output power		38	
Filter loss	1	37	
Cable loss	1	36	
Matching loss	1	35	
Radiated power		35	

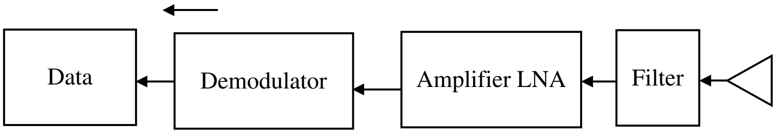

FIGURE 1.2 Receiver block diagram.

TABLE 1.7 Receiving Channel Power Budget

Component	Gain (dB)/Loss (dB)	Power (dBm)	Remarks
Input power		–20	
Receiver gain	23		
Cable loss	1	–21	
Filter loss	1	–22	
Matching loss	1	–23	
LNA amplifier output power		0	

1.7 PATH LOSS

Path loss is a reduction in the signal's power, which is a direct result of the distance between the transmitter and the receiver in the communication path.

There are many models used in the industry today to estimate the path loss, and the most common are the free-space and Hata models. Each model has its own requirements that need to be met in order to be utilized correctly. The free-space path loss is the reference point other models used.

1.7.1 Free-Space Path Loss

$$\text{Free-space path loss (dB)} = 20\log_{10} f + 20\log_{10} d - 147.56$$

where F is frequency in hertz and d is the distance in meters.

Free-space model typically underestimates the path loss experienced for mobile communications. Free-space model predicts point-to-point fixed path loss.

1.7.2 Hata Model

The Hata model is used extensively in cellular communications. The basic model is for urban areas, with extensions for suburbs and rural areas.

The Hata model is valid only for these following ranges:

- Distance 1–20 km
- Base height 30–200 m
- Mobile height 1–10 m
- 150–1500 MHz

The Hata formula for urban areas is

$$L_{\mathrm{H}} = 69.55 + 26.16\log_{10} f_{\mathrm{c}} - 13.82\log_{10} h_{\mathrm{b}} - \mathrm{env}(h_{\mathrm{m}}) + (44.9 - 6.55\log_{10} h_{\mathrm{b}})\log_{10} R$$

where

h_{b} is the base station antenna height in meters

h_{m} is the mobile antenna height also measured in meters

R is the distance from the cell site to the mobile in kilometers

f_{c} is the transmit frequency in MHz

env(h_{m}) is an adjustment factor for the type of environment and the height of the mobile (env(h_{m}) = 0 for urban environments with a mobile height of 1.5 m)

1.8 RECEIVER SENSITIVITY

Sensitivity describes the weakest signal power level that the receiver is able to detect and decode. Sensitivity is determined by the lowest SNR at which the signal can be recovered. Different modulation and coding schemes have different minimum SNRs.

Sensitivity is determined by adding the required SNR to the noise present at the receiver.

Noise sources

- Thermal noise
- Noise introduced by the receiver's amplifier

Thermal noise = $N = kTB$ (W)
where

$k = 1.3803 \times 10^{-23}$ J/K
T = temperature in Kelvin
B = receiver bandwidth

N (dBm) = $10\log_{10}(kTB) + 30$
Thermal noise is usually very small for reasonable bandwidths.

1.8.1 Basic Receiver Sensitivity Calculation

Sensitivity (W) = $kTB \times NF$ (linear) × minimum SNR required (linear)
Sensitivity (dBm) = $10\log_{10}(kTB \times 1000) + NF$ (dB) + minimum SNR required (dB)
Sensitivity (dBm) = $10\log_{10}(kTB) + 30 + NF$ (dB) + minimum SNR required (dB)

Sensitivity decreases in communication systems when:

- Bandwidth increases.
- Temperature increases.
- Amplifier introduces more noise.
- There are losses in space, rain, and snow.

1.9 RECEIVERS: DEFINITIONS AND FEATURES

Figure 1.3 presents a basic receiver block diagram.

1.9.1 Receiver

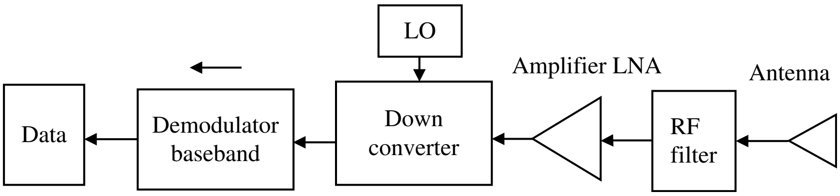

FIGURE 1.3 Basic receiver block diagram.

1.9.2 Receivers: Definitions

RF, IF, and LO frequencies—When a receiver uses a mixer we refer to the input frequency as the RF. The system must provide a signal to mix down the RF, and this is called the local oscillator. The resulting lower frequency is called the intermediate frequency (IF), because it is somewhere between the RF and the baseband frequency.

Baseband frequency—The baseband is the frequency at which the information you want to process is.

Preselector filter—Preselector filter is used to keep undesired radiation from saturating a receiver. For example, we don't want our cell phone to pick up air-traffic control radar.

Amplitude and phase matching versus tracking—In a multichannel receiver (more than one receiver), it is important for the channels to match and track each other over frequency. Amplitude and phase *matching* means that the relative magnitude and phase of signals that pass through the two paths must be almost equal.

Tunable bandwidth versus instantaneous bandwidth—*Instantaneous bandwidth* is what we get with a receiver when we keep the LO at a fixed frequency and sweep the input frequency to measure the response. The resulting bandwidth is a function of the frequency responses of everything in the chain. Their instantaneous bandwidth has a direct effect on the minimum detectable signal. Tunable bandwidth implies that we change the frequency of the LO to track the RF frequency. The bandwidth in this case is only a function of the preselector filter, the LNA, and the mixer. Tunable bandwidth is often many times greater than instantaneous bandwidth.

Gain—The gain of a receiver is the ratio of input signal power to output signal power.

Noise figure—Noise figure of a receiver is a measure of how much the receiver degrades the ratio of signal to noise of the incoming signal. It is related to the minimum detectable signal. If the LO signal has a high AM and/or FM noise, it could degrade the receiver noise figure because, far from the carrier, the AM and FM noise originate from thermal noise. Remember that the effect of LO AM noise is reduced by the balance of the balanced mixer.

1dB compression point—1dB compression point is the power level where the gain of the receiver is reduced by 1dB due to compression.

Linearity—The receiver operates linearly if a 1dB increase in input signal power results in a 1dB increase in IF output signal strength.

Dynamic range—Dynamic range of a receiver is a measurement of the minimum detectable signal to the maximum signal that will start to compress the receiver.

Signal-to-noise ratio (**S/N** or SNR)—SNR is a measure of how far a signal is above the noise floor.

Noise factor, noise figure, and noise temperature

- Noise factor is a measure of how the signal to noise ratio is degraded by a device:

  F = noise factor = $(S_{in}/N_{in})/(S_{out}/N_{out})$

  where

  S_{in} is the signal level at the input

  N_{in} is the noise level at the input

  S_{out} is the signal level at the output

  N_{out} is the noise level at the output

- The noise factor of a device is specified with noise from a noise source at room temperature ($N_{in} = KT$), where K is Boltzmann's constant and T is approximately room temperature in Kelvin. KT is somewhere around −174dBm/Hz. Noise figure is the noise factor, expressed in decibels:

  NF (dB) = noise figure = 10log (F).

  T = noise temperature = $290 \times (F - 1)$.

  1dB NF is about 75 K, and 3dB is 288 K.

  The noise factor contributions of each stage in a four-stage system are given in Equation 1.25:

$$F = F1 + \frac{F2-1}{G1} + \frac{F3-1}{G1G2} + \frac{F4-1}{G1G2G3} \tag{1.25}$$

1.10 TYPES OF RADARS

In **monostatic radars** the transmitting and receiving antennas are colocated. Most radars are monostatic.

In **bistatic radars** the transmitting and receiving antennas are not colocated.

Doppler radar is used to measure the velocity of a target due to its Doppler shift. Police radar is a classic example of Doppler radar.

Frequency-modulated/continuous-wave (**FMCW**) **radar** implies that the radar signal is "chirped" or its frequency is varied in time. By varying the frequency in this manner, you can gather both range and velocity information.

Synthetic aperture radar (SAR) uses a moving platform to "scan" the radar in one or two dimensions. Satellite radar images are mostly done using SAR.

1.11 TRANSMITTERS: DEFINITIONS AND FEATURES

Figure 1.4 presents a basic transmitter block diagram.

1.11.1 Transmitter

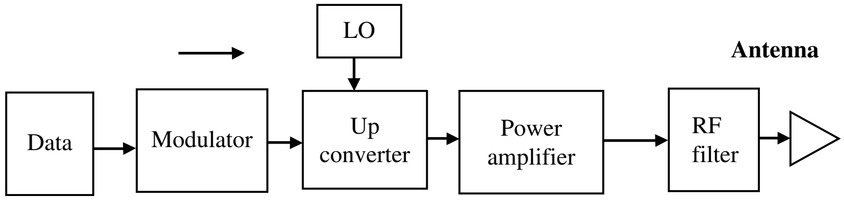

FIGURE 1.4 Transmitter block diagram.

1.11.2 Amplifiers

Class A—The amplifier is biased at close to half of its saturated current. The output conducts during all 360° of phase of the input signal sine wave. Class A does not give maximum efficiency, but provides the best linearity. Drain efficiencies of 50% are possible in class A.

Class B—The power amplifier is biased at a point where it draws nearly 0 DC current; for an FET, this means that it is biased at pinch-off during one half of the input signal sine wave it conducts, but not the other half. Class B amplifier can be very efficient, with theoretical efficiency of 80–85%. However, we are giving up 6dB of gain when we move from class A to class B.

Class C—Class C occurs when the device is biased so that the output conducts for even less than 180° of the input signal. The output power and gain decrease.

Power density—This is a measure of power divided by transistor size. In the case of FETs it is expressed in watts/millimeter. GaN transistors have more than 10 W/mm power density.

Saturated output power (PSAT) is the output power where the $P_{\text{in}}/P_{\text{out}}$ curve slope goes to zero.

Load pull—This is the process of varying the impedance seen by the *output* of an active device to other than 50 Ω in order to measure performance parameters, in the simplest case, gain. In the case of a power device, a load pull power bench is used to evaluate large signal parameters such as compression characteristics, saturated power, efficiency, and linearity as the output load is varied across the Smith chart.

Harmonic load pull—This is the process of varying the impedance at the output of a device, with separate control of the impedances at F_0, $2\,F_0$, $3\,F_0$,….

Source pull—This is the process of varying the impedance seen by the input of an active device to other than 50 Ω in order to measure performance parameters. In the case of a low-noise device, source pull is used in a noise parameter extraction setup to evaluate how SNR (noise figure) varies with source impedance.

TABLE 1.8 Power Amplifier Output Power Capabilities

Frequency Band	Solid State	Tube Type
L band through C band	200 W (LDMOS) GaN	
X band	50 W (GaN HEMT device)	3000 W (TWT)
Ka band	6 W (GaAs PHEMT device)	1000 W (klystron)
Q band	4 W (GaAs PHEMT device)	
W band	0.5 W (InP)	1000 W (EIKA) even more! (gyrotron)

Amplifier temperature considerations

In the case of an FET amplifier, the gain drops and the noise figure increases.

The gain drop is around −0.006dB/stage/°C.

Noise figure of an LNA increases by +0.006dB/°C. In an LNA, the first stage will dominate the temperature effect.

Power amplifiers

Power amplifiers are used to boost a small signal to a large signal.

Solid-state amplifiers and tube amplifiers are usually employed as power amplifiers.

Power amplifier output power capabilities are listed in Table 1.8.

REFERENCES

[1] ITU. *ITU-R Recommendation V.431: Nomenclature of the Frequency and Wavelength Bands Used in Telecommunications*. Geneva: International Telecommunication Union; 2000.

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[3] AFR 55-44/AR 105-86/OPNAVINST 3430.9A/MCO 3430.1, 27 October 1964 superseded by AFR 55-44/AR 105-86/OPNAVINST 3430.1A/MCO 3430.1A, 6 December 1978: Performing Electronic Countermeasures in the United States and Canada, Attachment 1, ECM Frequency Authorizations.

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