Chapter 3

Microwave Circuit and Systems

- Introduction
- Microwave circuit and systems
- Microwave transmitters and receivers

RF/Microwave Systems

- The audience is both graduate students of RF/microwave courses and practicing engineers in this industry.
- We expect you have already mastered the fundamentals (component definitions for amplifiers, oscillators, and mixers; two-port network theory, power gains, Smith chart matching, direct current (dc) biasing, etc.)
- The integration of **analog** and **digital** functions on the same silicon chip is expected to significantly reduce costs for all consumer products.

..... con'td

- The capacitor of **1000 pF** in parallel with the headphones is an RF ground for the carrier frequency.
- The headphones detect the envelope of the received signal, which is the desired information.
- This type of receiver is the simplest of all, and there are numerous web sites which can sell you one for your evaluation.

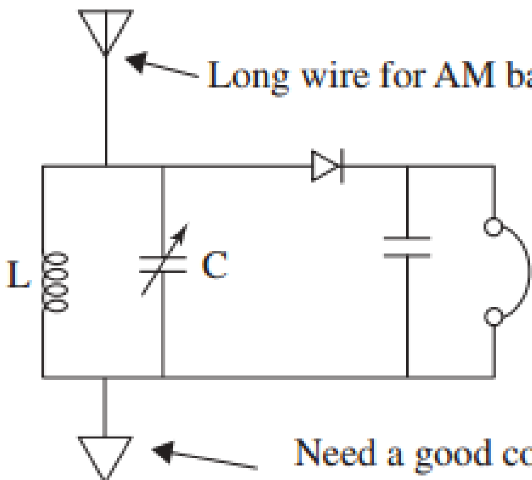
- A similar invention which also uses **no battery** is the telephone.
- The detector is a diaphragm which transmits sound to the human ear drum, which has a threshold sensitivity of one hydrogen atom displacement, where the frequency is roughly **5 kHz**.

..... con'td

- The frequency spectrum of a receiver is shown in Figure 3.2, where the image signal may also produce an unwanted IF output, so the image should be filtered.
- The image signal is the mirror image of the desired **RF signal**.

- The radio is a tuned resonant tank circuit at the carrier frequency, which maximizes the input voltage to the heterodyne receiver shown in Figure 3.3.
- The incoming signal is converted to a lower intermediate frequency (IF) by the local oscillator (LO), where the pertinent mathematics is

$$\cos\alpha\cos\beta = 0.5\cos(\alpha-\beta) + 0.5\cos(\alpha+\beta)$$
$$= 0.5\cos(\omega_{IF}t) + 0.5\cos(\omega_{RF}t + \omega_{LO}t)$$



Long wire for AM band

L: Approx. 250 µH

C: Approx. 40-400pF to tune AM band

Headphones need to be high-Z (> a few kΩ)

Need a good connection to earth ground for best results
(The ground terminal of an AC power outlet often works okay, but be sure to hook things upright, or there could be some measure of unpleasantness)

Figure 3.1 Crystal radio receiver or Foxhole Radio

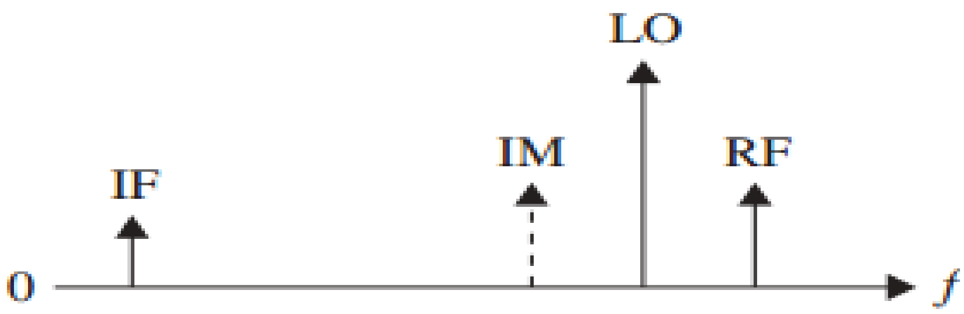
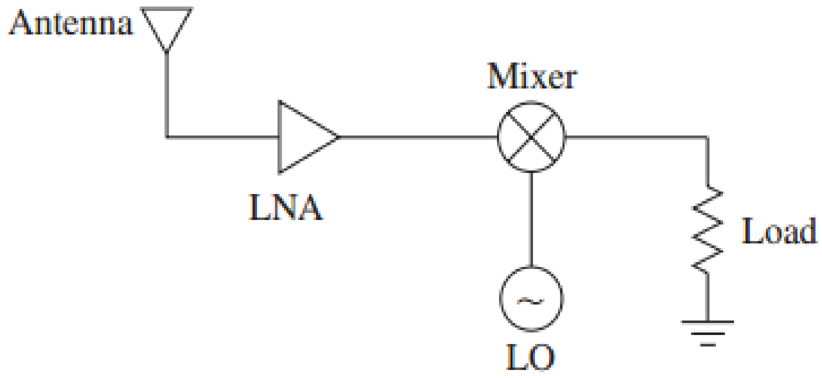
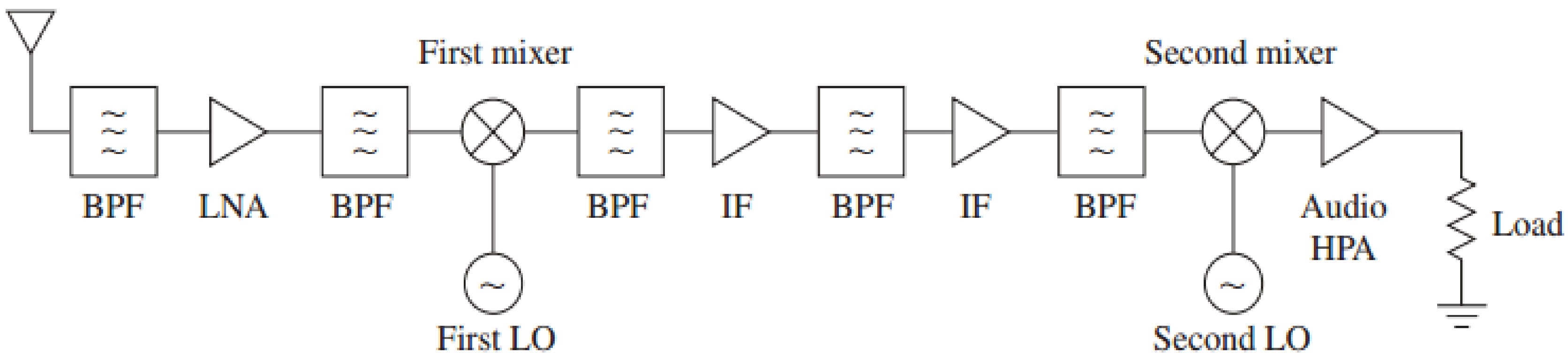


Figure 3.2 Frequency spectrum of radio receiver.



(*a*) Heterodyne receiver, if $f_{LO} = f_{RF}$, homodyne or direct-conversion receiver



(*b*) Superheterodyne receiver

Figure 3.3 Heterodyne receiver, single-conversion super heterodyne receiver, double conversion super heterodyne receiver

..... con’td

Where **α** and **β** are the **RF** and **LO** frequencies. The frequency spectrum is shown in Figure 3.2, where the image signal may also produce an unwanted IF output, so the image should be filtered. The image signal is the **mirror image** of the desired RF signal.

The basic heterodyne receiver invented by Armstrong in **1917** is given in Figure 3.3. The modulated carrier is amplified, converted to an IF, demodulated, and amplified at baseband (audio). This gives a single tuning control (the LO) and allows high gain and selectivity at the IF.

A super heterodyne receiver has **two (or more**) **mixers**, so the frequency is converted **once** or **twice** to a lower frequency. Most of the gain is done at the **first** or **second IF**, where the cost is generally lower.

Most electrical engineers have worked in various aspects of **RF** or **microwave design**. The circuits are organized into three frequency ranges:

..... con’td

RF	1 MHz (or less) to 1 GHz
Microwave	1–30 GHz
Millimeter wave	30–300 GHz (or higher)

The word wireless was used by Marconi in 1901, and it reoccurred as a replacement for the word radio in about **1991.** The design techniques tend to be different for these **three groups**, but there are many similarities. Such as an soft Design Suite, **ADS** (Advanced Design System), or Advanced Wave Research **(AWR)** Microwave Office (**MWO)** may be used for all three groups.

Another summary of wireless applications is given in Table 3.1. These applications include all **three frequency groups** as well as communications, radar, navigation, remote sensing, RF identification, broadcasting, automobiles and highways, sensors, surveillance, medical, and astronomy and space exploration.

Table 3.1 Wireless Applications

1.Wireless communications: space, long-distance, cordless phones, cellular telephones, mobile, PCS, local-area networks (LANs), aircraft, marine, citizen's band (CB) radio, vehicle, satellite, global, etc.

2.Radar (standing for radio detection and ranging): airborne, marine, vehicle, collision avoidance, weather, imaging, air defense, traffic control, police, intrusion detection, weapon guidance, surveillance, etc.

3.Navigation: microwave landing system (MLS), global positioning system (GPS), beacon, terrain avoidance, imaging radar, collision avoidance, auto-pilot, aircraft, marine, vehicle, etc.

4.Remote sensing: Earth monitoring, meteorology, pollution monitoring, forest, soil moisture,
vegetation, agriculture, fisheries, mining, desert, ocean, land surface, clouds, precipitation, wind, flood, snow, iceberg, urban growth, aviation and marine traffic, surveillance, etc.

5.RF identification: security, antitheft, access control, product tracking, inventory control, keyless entry, animal tracking, toll collection, automatic checkout, asset management, etc.

6.Broadcasting: amplitude- and frequency-modulated (AM, FM) radio, TV, direct broadcast satellite (DBS), universal radio system, etc.

7. Automobiles and highways: collision warning and avoidance, GPS, blind-spot radar, adaptive cruise control, auto navigation, road-to-vehicle communications, automobile communications, near-obstacle detection, radar speed sensors, vehicle RF identification, intelligent vehicle and highway system (IVHS), automated highway, automatic toll collection, traffic control, ground penetration radar, structure inspection, road guidance, range and speed detection, vehicle detection, etc.

8.Sensors: moisture sensors, temperature sensors, robotics, buried-object detection, traffic monitoring, antitheft, intruder detection, industrial sensors, etc.

9.Surveillance and electronic warfare: spy satellites, signal or radiation monitoring, troop movement, jamming, anti jamming, police radar detectors, intruder detection, etc.

10.Medical: magnetic resonance imaging, microwave imaging, patient monitoring, etc.

11.Radio astronomy and space exploration: radio telescopes, deep-space probes, space monitoring, etc.

12.Wireless power transmission: space-to-space, space-to-ground, ground-to-space, ground-to ground power transmission.

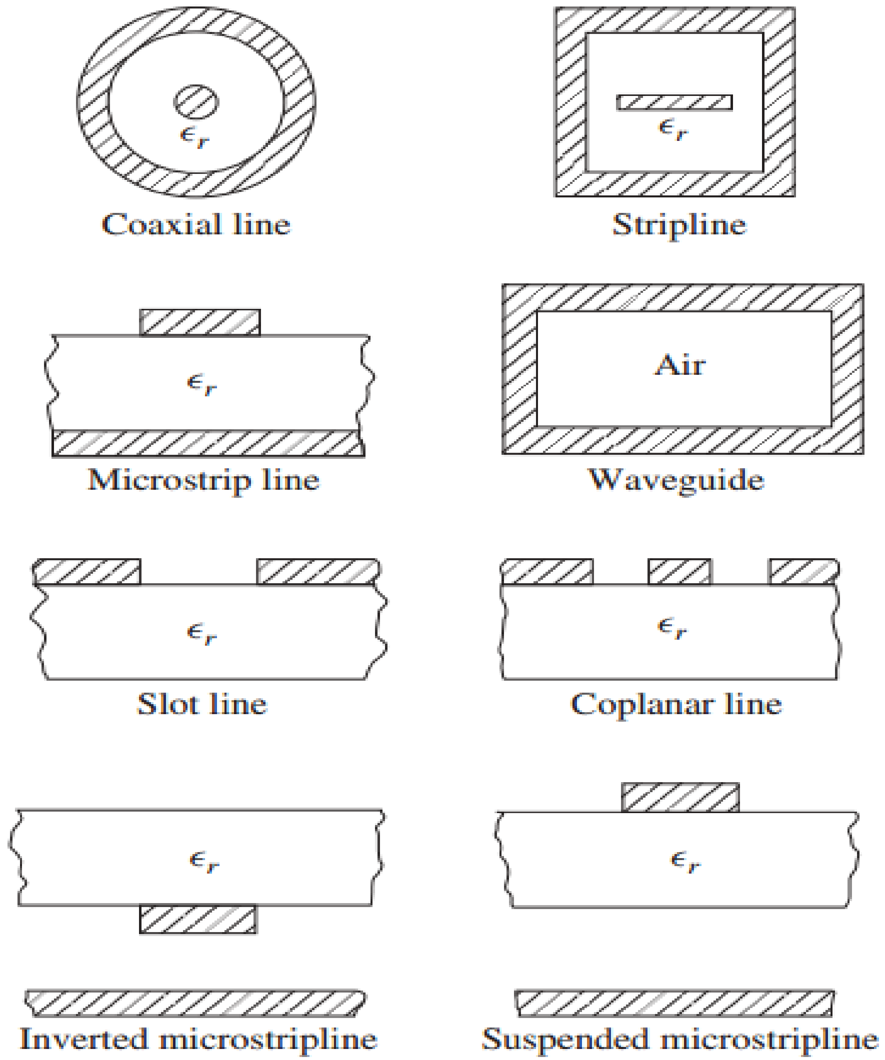


Figure 3.4 Geometry for microwave transmission.

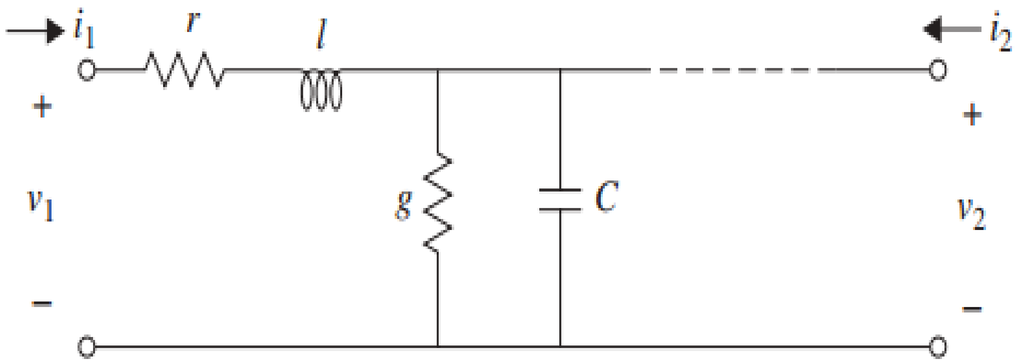


Figure 3.5 Lumped-element equivalent circuit of transmission line.

Transmission lines may be modeled as in Figure 3.5, which leads to the telegrapher equations, which are a time-domain description of the line:

….. con’td

$$\frac{\partial v(z,t)}{\partial z} = -RI(z,t) - L\frac{\partial I(z,t)}{\partial t}$$

$$\frac{\partial I(z,t)}{\partial z} = -Gv(z,t) - C\frac{\partial v(z,t)}{\partial t}$$

For sinusoidal steady-state conditions, this may be simplified to

$$\frac{dV(z)}{dz} = -(R + j\omega L)I(z)$$

$$\frac{dI(z)}{dz} = -(G + j\omega C)V(z)$$

which is noted to be very similar to Maxwell’s curl equations:

$$\nabla \times E = -j\omega\mu H$$

$$\nabla \times H = j\omega\varepsilon E$$

..... con’td

Combining the telegrapher equations leads to

$$\frac{d^2V(z)}{dz^2} - \gamma^2 V(z) = 0$$

$$\frac{d^2I(z)}{dz^2} - \gamma^2 I(z) = 0$$

where

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}$$

is the complex propagation constant, which is a function of frequency. Traveling-wave solutions can be found as

$$V(z) = V_0^+ e^{-\gamma \cdot z} + V_0^- e^{\gamma \cdot z}$$

$$I(z) = I_0^+ e^{-\gamma \cdot z} + I_0^- e^{\gamma \cdot z}$$

..... con’td

With a few more steps, we may obtain the voltage waveform in the time domain as

$$V(z,t) = |V_0^+| \cos(\omega t - \beta z + \phi^+) e^{-\alpha z} + |V_0^-| \cos(\omega t + \beta z + \phi^-) e^{-\alpha z}$$

where $\phi^{\pm}$ is the phase angle of the complex voltage $V_0^{\pm}$. The wavelength on the line is

$$\lambda = \frac{2\pi}{\beta}$$

and the phase velocity is

$$v_p = \frac{\omega}{\beta} = \lambda f$$

where the actual time delay must be calculated using the group velocity, defined by

$$v_g = \frac{d\omega}{d\beta}$$

For a TEM wave, these two velocities are the same.

RF Wireless/Microwave/Millimeter-wave Applications

- The primary applications of the three frequency groups are essentially the same: **communications receivers and transmitters** (or transceivers).
- The simplest example to envision is your cellular telephone at 8**50 MHz** or **1.85** GHz. The essential components are the **amplifiers, oscillators, and mixers**.

- Amplifier, oscillator, and mixer functions will use the lowest cost transistors which satisfy the specifications. The oscillators use the same low-cost transistors with the additional requirement of low phase noise.
- The material properties and manufacturing methods presently favor silicon-based devices due to lower 1/f flicker noise, but this could change quickly.
- Designers of amplifiers and oscillators are usually the same engineers using the same software, transistors, and circuit technology; however, oscillator designers also need a high-Q resonator.

- The basic cellular RF wireless transceiver is shown in Figure 3.5. The circuits are basically the same for both analog and digital modulation, with most customers moving to digital modulation [time division multiple access (**TDMA**), frequency division multiple access (**FDMA**), and **CDMA**. The transceiver is also the same in all frequency bands, even at **100 GHz**.

- The cellular telephone is a **full duplex transceiver**, meaning the send and receive functions are both on all of the time. Starting at the antenna, there is a duplex filter which feeds the receiver, which consists of a preamplifier, an additional filter, and a mixer.
- The **duplexer** is optimized more for separating transmit and receive signals, which are typically **50 MHz** apart, rather than extreme selectivity.
- The front end is followed by a surface acoustic wave (SAW) filter which **reduces** the **image frequency**.
- These are high-impedance filters (about 150Ω to 1kΩ), not 50Ω.

..... con’td

- The transmit portion consists of an independent synthesizer that is modulated. There are dual-synthesizer chips available to accommodate this.
- Both **receive** and **transmit** frequencies are controlled by a **miniature temperature-compensated crystal oscillator.**
- One of its outputs is the system master clock for all digital activities. The output of the voltage-controlled oscillator (VCO) is then amplified and fed to the antenna through the same duplex filter as the receive portion.

- A useful way to categorize the applications is to list some everyday products which the consumer uses (Table 3.2). Today there are very few applications in the millimeter wave range, but the potential is obvious.
- All of these applications use transistors, passive components, duplexers, switches, attenuators, amplifiers, oscillators, mixers, and so on.

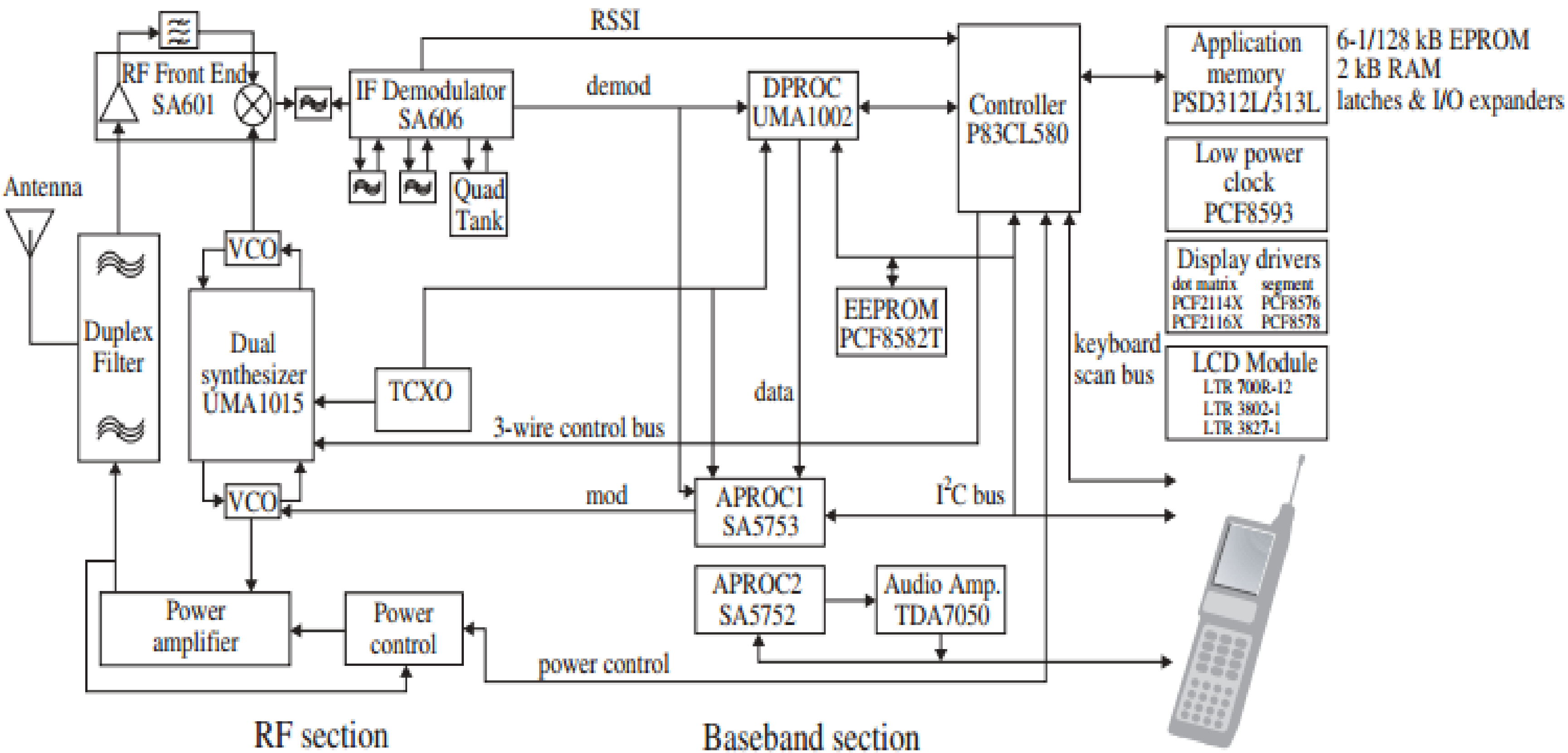


Figure 3.5 Cellular telephone

Table 3.2 Applications

RF/Wireless	Microwave	Millimeter Wave
AM radio, 1 MHz	Ultrahigh frequency (UHF) TV, 300 MHz–1 GHz	LMDS (local multiple-distribution systems), 30 GHz
FM radio, 100 MHz	Microwave oven, 2.45 GHz	Communication at maximum attenuation, 60 GHz
Very high frequency (VHF) TV, 45–300 MHz	Cellular Telephone, 850 MHz and 1.85 GHz	Communication at minimum attenuation, 10 and 94 GHz
		Optical Communication at 40 GHz and above
	Bluetooth, 2.45 GHz	Laser frequency, typically 300,000 GHz
	Wireless Video, 2.45 GHz	Ultra wideband, 60–66 GHz
	COFDM (coherent orthogonal frequency division multiplexed), 5.25 GHz	
Cordless Telephone, 50 MHz	Ultra wideband, 3–10 GHz	
Garage/auto openers, 1–5 MHz		

Frequency Bands, Modes, and Waveforms of Operation

A useful list of the frequency bands is given in Table 3.3. As the frequency moves up, the wavelength of sinusoidal signals reduces and the bandwidth in hertz of the communications systems continues to **increase**, including **optical circuits**.

Analog and Digital Requirements

- **Analog signals** travel continuously in real time, so it is very difficult to multiplex signals to increase the number of customers on the frequency band.
- For digital signals, there are many ways of multiplexing the signals so several customers receive communications simultaneously over the same frequency band.

- This is one of the foremost advantages of **digital communication** systems. The process of converting analog signals to digital format uses high-speed sampling analog-to-digital converter (ADC) circuits.
- Once the signals are in the digital domain, it becomes very easy to multiplex the information.

- In addition, **signal processing** can be done using digital signal processing (DSP) circuits to perform filtering, interpolation, and so on.
- Once the above techniques are performed, high-speed digital-to-analog converter (DAC) circuits may be used to reconstitute the original analog signal.

..... con’td

- ✓ Another feature of digital communications is **error correction**, which is not possible in analog communications.
- ✓ **Analog signals** may fade or become lost in the noise intermittently; with digital computer data, the **digital format** allows the information to be corrected for transmission errors, the accuracy is essentially 100%.

- ✓ **Analog signals** are basically **AM** or **FM** (wider bandwidth). Digital signals are usually phase modulated (**PM**, which is also wide bandwidth).
- ✓ The phase of each digital carrier pulse contains the baseband information. PM and FM are both forms of angle modulation, where one is the derivative of the other,

$$f = \frac{d\phi}{dt}$$

The three most important forms of digital multiplexed signals

- **TDMA** means each user is sharing the same frequency with his or her own time slot, typically eight users on the same frequency (for GSM).
- **FDMA** means the carrier frequency is hopping in a pattern known by the transmitter and receiver.
- **CDMA** means the entire bandwidth is shared by all users, who have orthogonal signals which do not interfere with each other. The bandwidth for CDMA is **1.25 MHz**, and it has increased to **5.0 MHz** for WCDMA.

- Presently the cellular telephone systems in the United States at 850 MHz and 1.85 GHz are roughly equally divided between TDMA and CDMA.
- Since both forms of multiplexing are constantly improving, the dominant choice has not been clearly found (if there is one).

The process of converting an analog signal to a digital bit stream is shown in Figure 3.6 .The analog signal is sampled by an ADC, modulated to convert the digital bit stream into a transmittable form, typically pulses of current, and finally transmission or signal processing, which usually includes multiplexing, as shown in Figure 3.7.

- The **sampling rate** must be **twice** the period of the **highest frequency** due to the Nyquist sampling theorem.
- For voice with an upper frequency of 4kHz for telephones,

$$T = \frac{1}{f} = \frac{1}{4(10^3)} = 0.25 \text{ ms}$$

So the sampling rate must be faster than 0.125 ms.

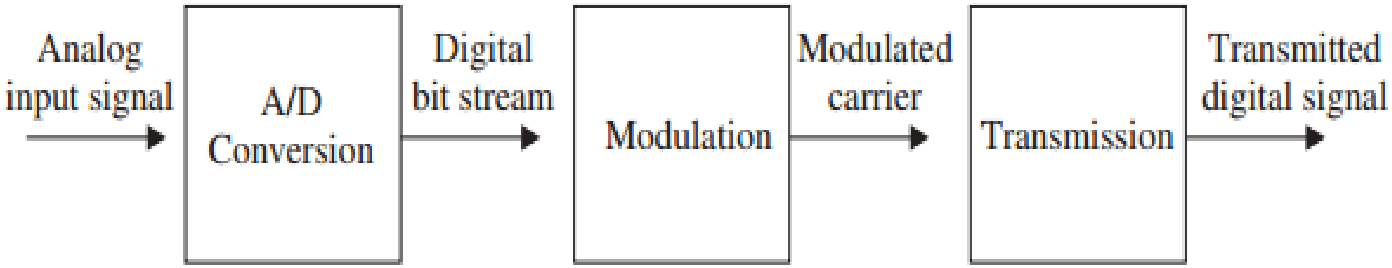


Figure 3.6 Block diagram of the digital communication process

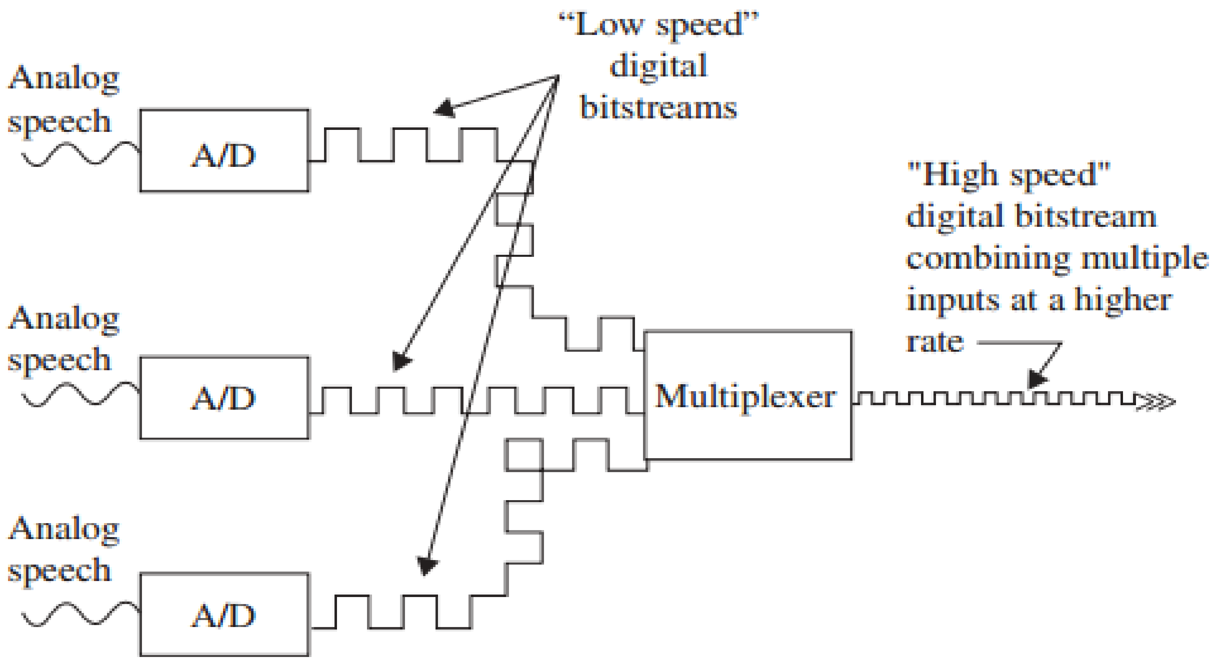


Figure 3.7 Multiplexing TDMA

Table 3.3 IEEE 802.11 Standards for Unlicensed Communications

Standard	Carrier	Modulation	Maximum Data Rate	Bandwidth	P_{max}
802.11b	2.4 GHz	CDMA	11 Mbps	83 MHz	1 W
802.11a	5.15–5.35 GHz	COFDM	54 Mbps	200 MHz	50 mW
	5.725–5.825 GHz	COFDM	54 Mbps	100 MHz	250 mW

- Another very important concept is the Friis transmission equation, which discusses the range of the communication system.
- Consider the simplest communications system shown in Figure 3.8.
- The transmitter with a power of Pt is fed into a transmitting antenna with a gain of Gt. The received power is Pr at a distance of R. The received power **density** can be calculated assuming no atmospheric losses, mismatch losses, and so on, as

$$S_D = \frac{P_t}{4\pi R^2} G_t \quad (\mathrm{W/m^2})$$

The received power is the power density multiplied by the effective area of the receiving antenna (which is related to the antenna gain)

$$P_r = \frac{P_t G_t}{4\pi R^2} A_{er} \qquad \text{(W)}$$

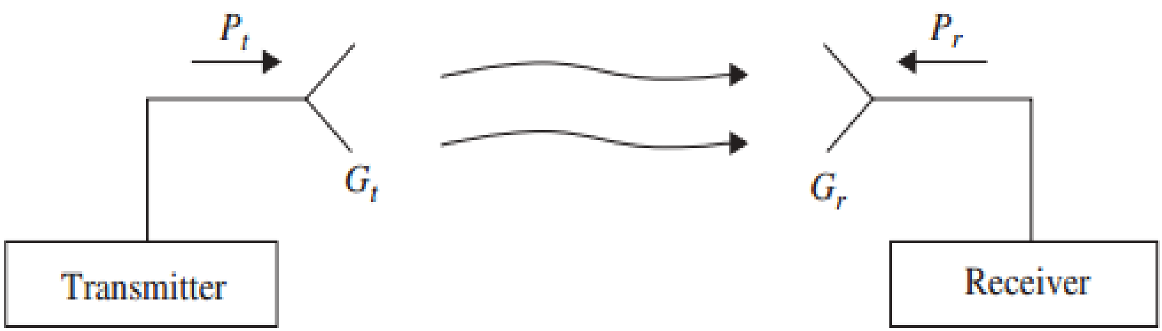


Figure 3.8 Simplified wireless communication system

..... con’td

$$A_{er} = \frac{G_r \lambda_0^2}{4\pi}$$

Substituting gives the Friis power transmission equation:

$$P_r = \frac{P_t G_t G_r \lambda_0^2}{(4\pi R)^2}$$

which can also be put in the form

$$\frac{P_L}{P_T} = \frac{k A_{et} A_{er}}{\lambda_0^2 R^2}$$

where k is an efficiency factor, generally 0.4 to 0.7, which accounts for factors such as misalignment, polarization mismatch, impedance mismatch, and atmospheric losses, and it is also called $1/L_{\mathrm{sys}}$.

If $P_r = S_{i,\min}$, the minimum detectable signal required for the system, we have the maximum range

$$R_{\max} = \left[\frac{P_t G_t G_r \lambda_0^2}{(4\pi)^2 S_{i,\min} L_{\text{sys}}} \right]^{1/2}$$

This is a very important result for understanding the many components which constitute the communication system or wireless system.

An example will illustrate these concepts. Consider a transmitter at 2 GHz,

$$\lambda_0 = 15 \text{ cm} = 0.15 \text{ m} \qquad G_t = 10 \text{ dB} \qquad P_t = 1 \text{ W}$$

sending to a receiver with

$$G_r = 10 \text{ dB} \qquad S_{i\,\min} = -90 \text{ dBm} = -120 \text{ dBW} = 10^{-12} \text{ W} \qquad L_{\text{sys}} = 1$$

The maximum range is

$$\mathrm{R}_{\max} = \left(\frac{1 \times 10 \times 10 \times (0.15)^2}{(4\pi)^2 \times 10^{-12}} \right)^{1/2}$$

$$= (1.42 \times 10^{10})^{1/2} = 119 \times 10^3 \text{ m}$$

- The **range increases** as the square root of the **transmitted power increases**.
- The frequency dependence indicates **lower λ_0** or **higher frequency** will increase the **maximum range**.
- It is this property, more than any other, that makes **microwaves** and **millimeter waves** so important for **communication** and **radar systems**.
- Another important observation is the difference between coaxial transmission and antenna-to-antenna transmission, shown in Figure 3.9

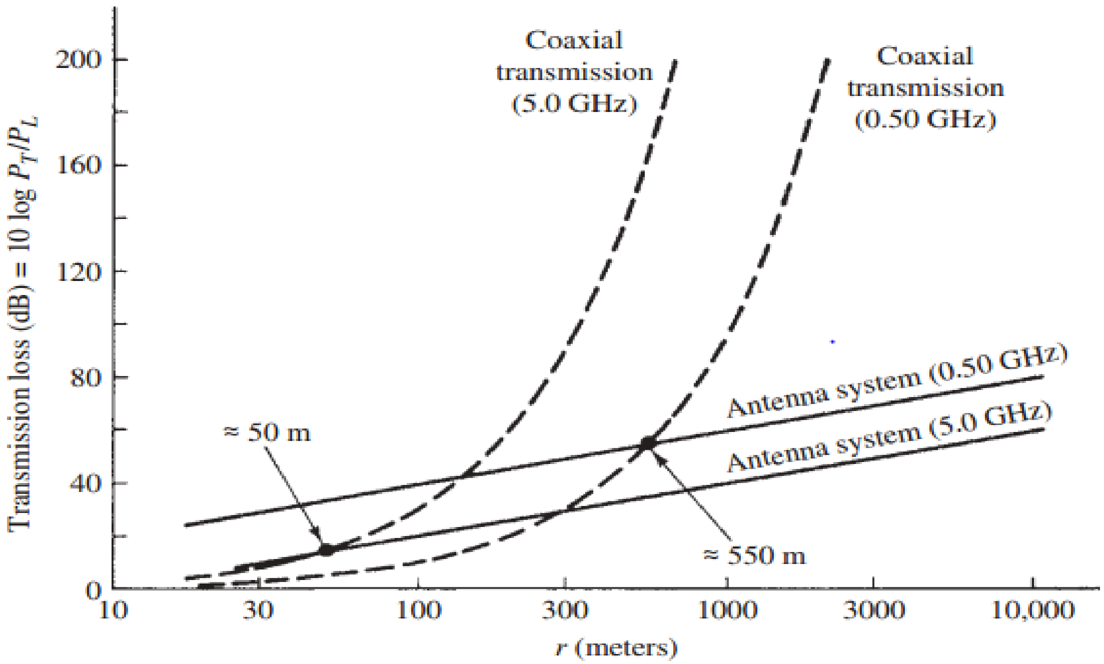


Figure 3.9 Attenuation for coaxial and antenna system communications

Basic RF Transmitters and Receivers

- This could be an **AM radio receiver** for the commercial AM broadcast band. The signal is twice down-converted to the low-cost 10.7MHz IF band, amplified, detected, and amplified again in the audio band (0 to 8 kHz).
- The characteristics of interest include power output and operating frequency, efficiency, power output variation, frequency tuning range, stability, oscillator quality factor (Qu), noise (AM, FM, and phase noise), spurious signals, frequency variations due to frequency jumping, frequency pulling (load variations), frequency pushing (DC supply variations), and posttuning drift (frequency and power variations due to heating of a solid-state device).

Oscillator noise is defined by

$$\mathcal{L}(f_m) = \frac{\text{noise power in 1-Hz bandwidth at } f_m \text{ offset from carrier}}{\text{carrier signal power}} = \frac{N}{C}$$

$$= 10 \log\left(\frac{N}{C}\right) \qquad \text{dBc/Hz}$$

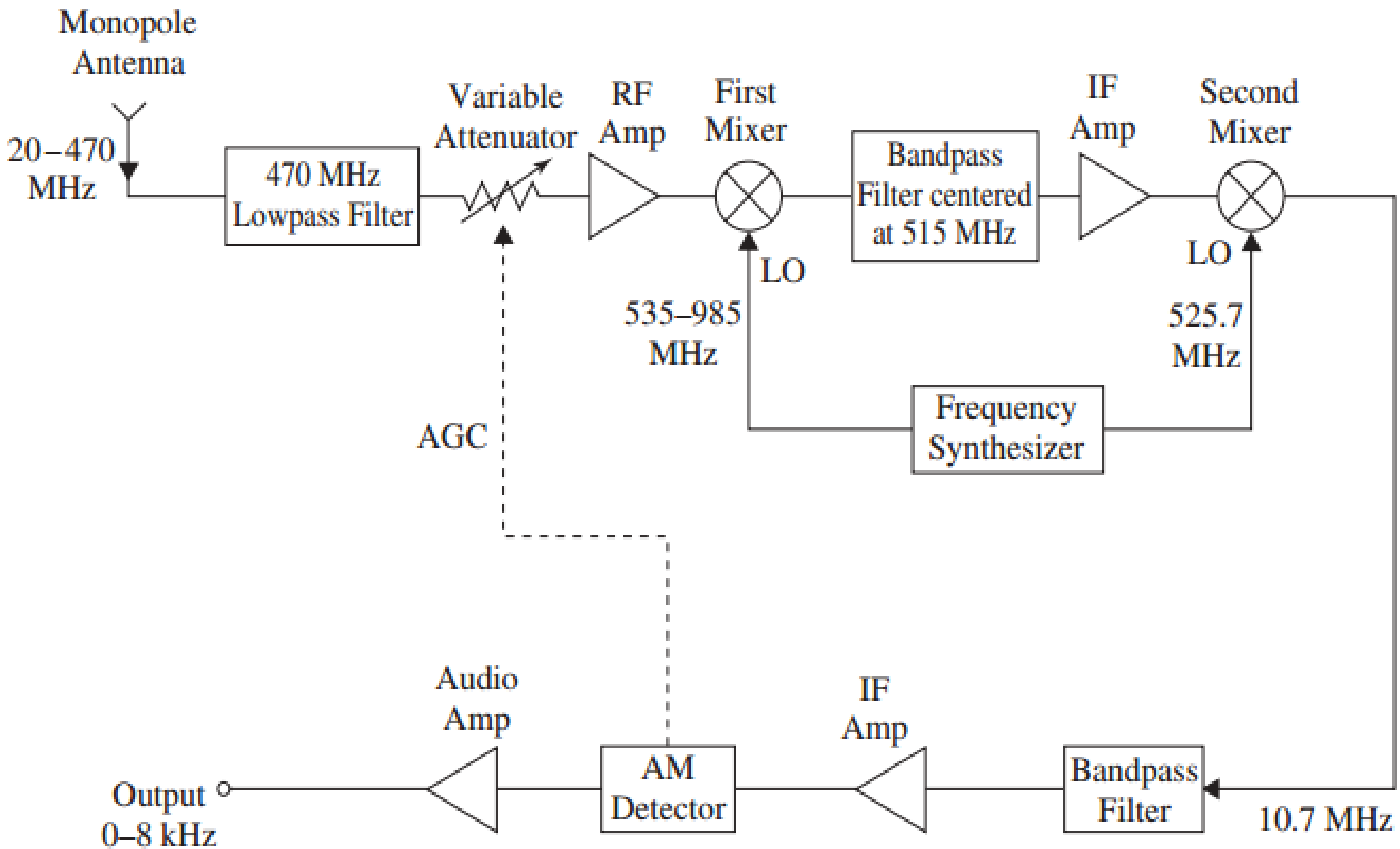


Figure 3.10 Typical radio receiver

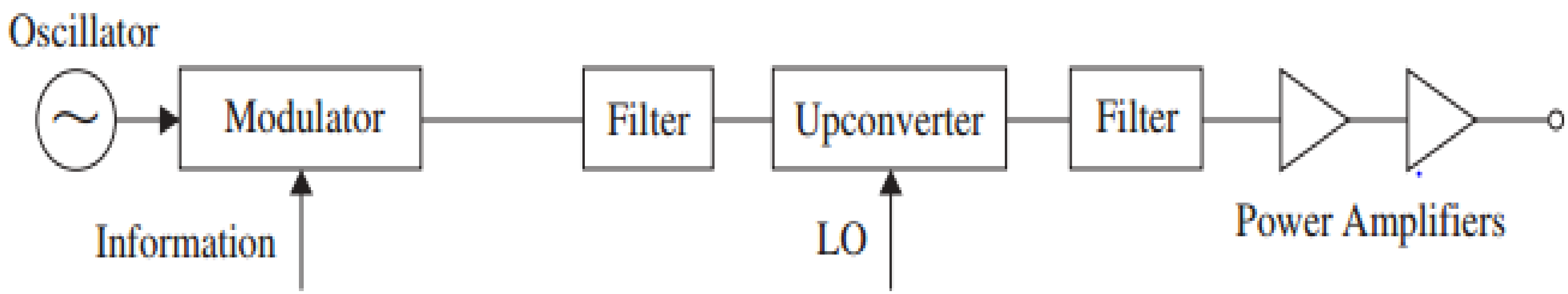


Figure 3.11 Transmitter system

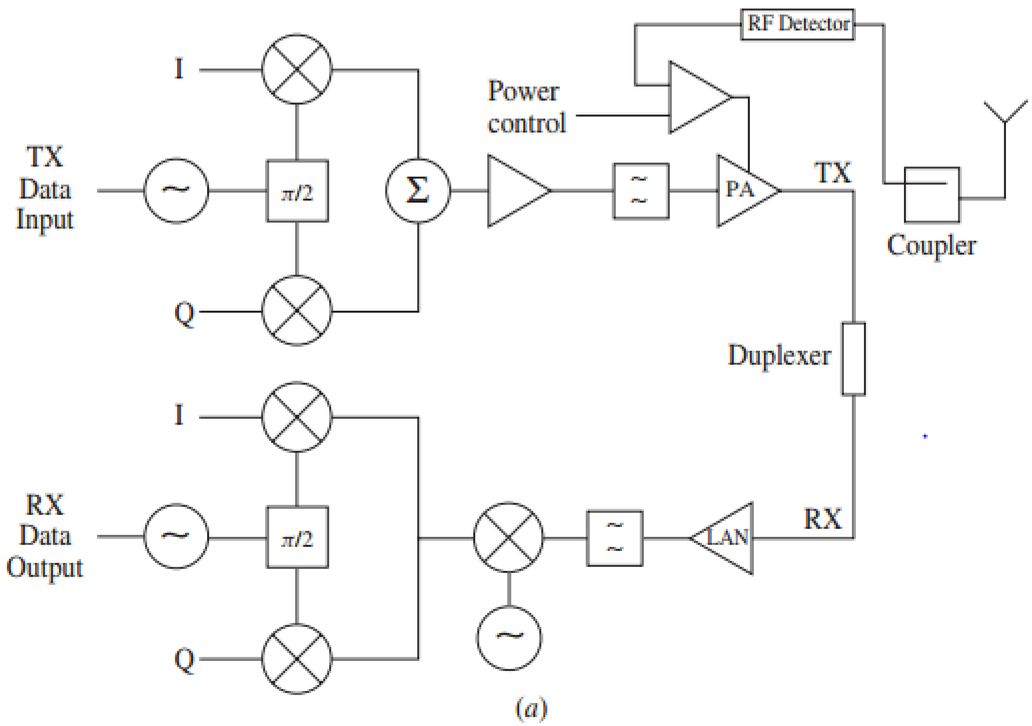


Figure 3.12 (a) Simplified transceiver block diagram for wireless communications

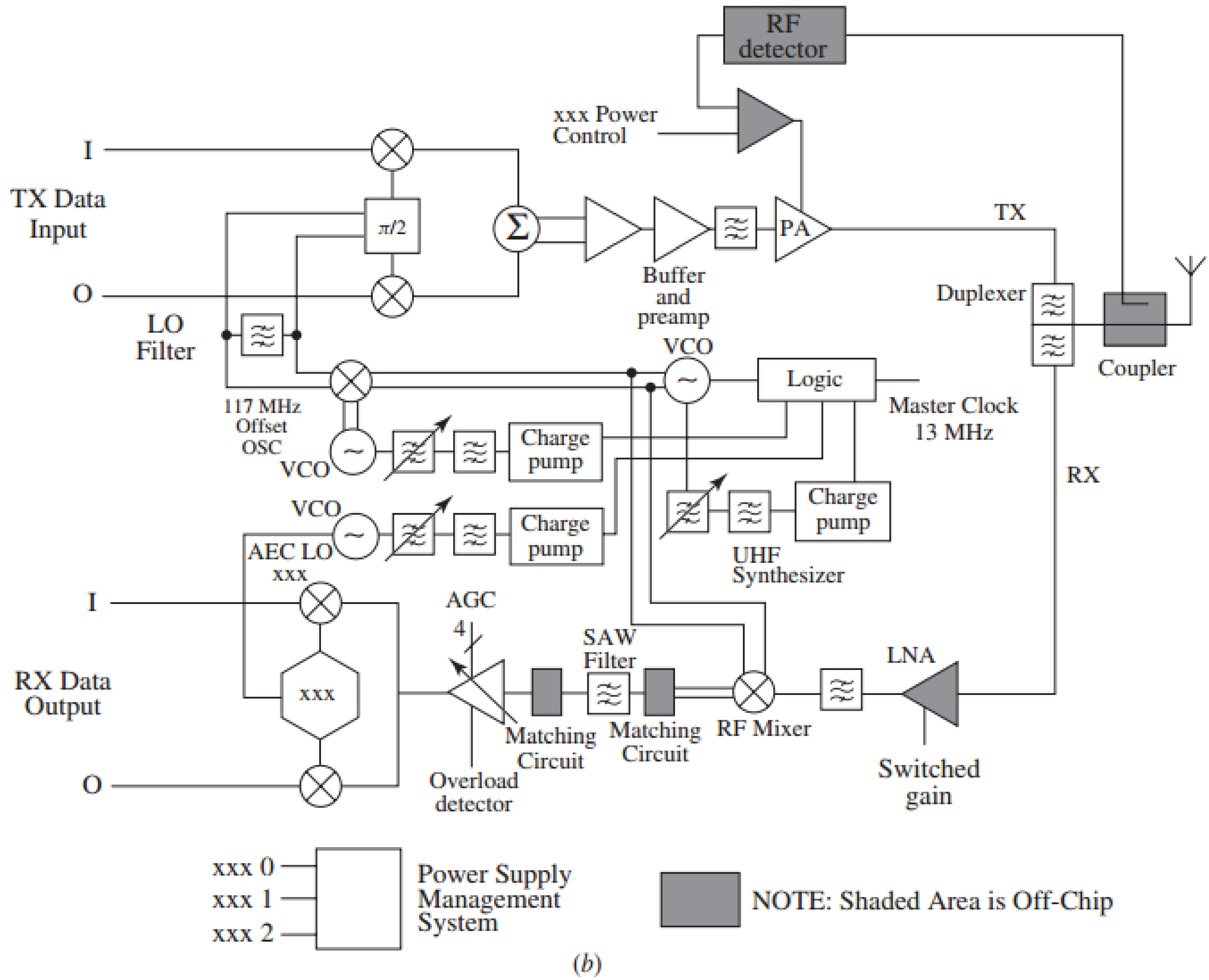


Figure 3.13(b) Typical mobile phone systems.