RF and Microwave Wireless Systems. Kai Chang

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CHAPTER ELEVEN

Other Wireless Systems

The two major applications of RF and microwave technologies are in communications and radar/sensor systems. Radar and communication systems have been discussed in Chapters 7 and 8, respectively. There are many other applications such as navigation and global positioning systems, automobile and highway applications, direct broadcast systems, remote sensing, RF identification, surveillance systems, industrial sensors, heating, environmental, and medical applications. Some of these systems will be discussed briefly in this chapter. It should be emphasized that although the applications are different, the general building blocks for various systems are quite similar.

11.1 RADIO NAVIGATION AND GLOBAL POSITIONING SYSTEMS

Radio navigation is a method of determining position by measuring the travel time of an electromagnetic (EM) wave as it moves from transmitter to receiver. There are more than 100 different types of radio navigation systems in the United States. They can be classified into two major kinds: active radio navigation and passive radio navigation, shown in Figs. 11.1 and 11.2.

Figure 11.1 shows an example of an active radio navigation system. An airplane transmits a series of precisely timed pulses with a carrier frequency f_1. The fixed station with known location consists of a transponder that receives the signal and rebroadcasts it with a different frequency f_2. By comparing the transmitting and receiving pulses, the travel time of the EM wave is established. The distance between the aircraft and the station is

$$d = c(\tfrac{1}{2} t_R) \tag{11.1}$$

where t_R is the round-trip travel time and c is the speed of light.

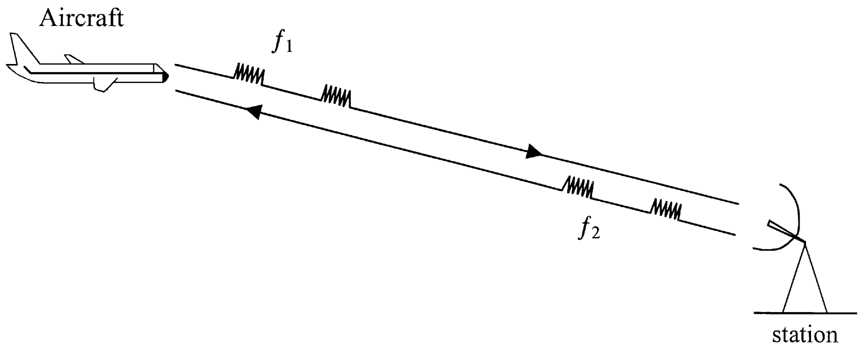


FIGURE 11.1 Active radio navigation system.

In a passive radio navigation system, the station transmits a series of precisely timed pulses. The aircraft receiver picks up the pulses and measures the travel time. The distance is calculated by

$$d = ct_R \tag{11.2}$$

where t_R is the one-way travel time.

The uncertainty in distance depends on the time measurement error given in the following:

$$\Delta d = c\,\Delta t_R \tag{11.3}$$

If the time measurement has an error of 10^{-6} s, the distance uncertainty is about 300 m.

To locate the user position coordinates, three unknowns need to be solved: altitude, latitude, and longitude. Measurements to three stations with known locations will establish three equations to solve the three unknowns. Several typical radio navigation systems are shown in Table 11.1 for comparison. The Omega

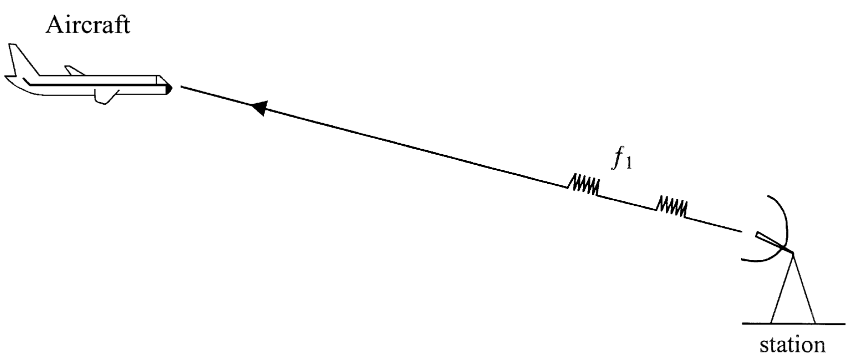


FIGURE 11.2 Passive radio navigation system.

TABLE 11.1 Comparison of Radio Navigation Systems

System	Position Accuracy, m[a]	Velocity Accuracy, m/sec	Range of Operation	Comments
Global Positioning Systems, GPS	16 (SEP)	≥ 0.1 (rms per axis)[b]	Worldwide	24-h all-weather coverage; specified position accuracy available to authorized users
Long-Range Navigation, Loran C[c]	180 (CEP)	No velocity data	U.S. coast and continental, selected overseas areas	Localized coverage; limited by skywave interference
Omega	2200 (CEP)	No velocity data	Worldwide	24-h coverage; subject to VLF propagation anomalies
Standard inertial navigation systems, Std INS[d]	≤ 1500 after 1st hour (CEP)	0.8 after 2 h (rms per axis)	Worldwide	24-h all-weather coverage; degraded performance in polar areas
Tactical Air Navigation, Tacan[c]	400 (CEP)	No velocity data	Line of sight (present air routes)	Position accuracy is degraded mainly by azimuth uncertainty, which is typically on the order of 1.0°
Transit[c]	200 (CEP)	No velocity data	Worldwide	90-min interval between position fixes suits slow vehicles (better accuracy available with dual-frequency measurements)

[a]SEP, CEP = spherical and circular probable error (linear probable error in three and two dimensions).
[b]Dependent on integration concept and platform dynamics.
[c]Federal Radionavigation Plan, December 1984.
[d]SNU-84-1 *Specification for USAF Standard Form Fit and Function* (F^3) Medium Accuracy Inertial Navigation Set/Unit, October 1984.
Source: From reference [1], with permission from IEEE.

system uses very low frequency. The eight Omega transmitters dispersed around the globe are located in Norway, Liberia, Hawaii, North Dakota, Diego Garcia, Argentina, Australia, and Japan. The transmitters are phase locked and synchronized, and precise atomic clocks at each site help to maintain the accuracy. The use of low frequency can achieve wave ducting around the earth in which the EM waves bounce back and forth between the earth and ionosphere. This makes it possible to use only eight transmitters to cover the globe. However, the long wavelength at low frequency provides rather inaccurate navigation because the carrier cannot be modulated with useful information. The use of high-frequency carrier waves, on the other hand, provides better resolution and accuracy. But each transmitter can cover only a small local area due to the line-of-sight propagation as the waves punch through the earth's ionosphere. To overcome these problems, space-based satellite systems emerged. The space-based systems have the advantages of better coverage, an unobstructed view of the ground, and the use of higher frequency for better accuracy and resolution.

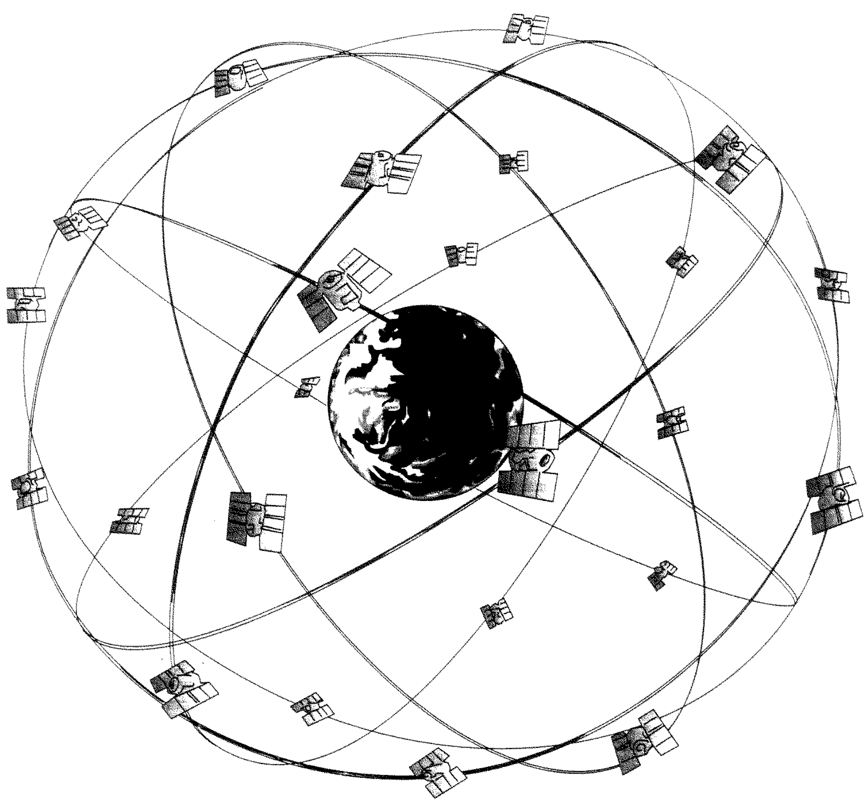


FIGURE 11.3 Navstar global positioning system satellite. (From reference [1], with permission from IEEE.)

The 24 Navstar global positioning satellites have been launched into 10,898 nautical mile orbits (approximately 20,200 km, 1 nautical mile = 1.8532 km) in six orbital planes. Four satellites are located in each of six planes at 55° to the plane of the earth's equator, as shown in Fig. 11.3. Each satellite continuously transmits pseudorandom codes at two frequencies (1227.6 and 1575.42 MHz) with accurately synchronized time signals and data about its own position. Each satellite covers about 42% of the earth.

The rubidium atomic clock on board weighs 15 lb, consumes 40 W of power, and has a timing stability of 0.2 parts per billion [2]. As shown in Fig. 11.4, the timing signal from three satellites would be sufficient to nail down the receiver's three position coordinates (altitude, latitude, and longitude) if the Navstar receiver is synchronized with the atomic clock on board the satellites. However, synchronization of the receiver's clock is in general impractical. An extra timing signal from the fourth satellite is used to solve the receiver's clock error. The user's clock determines a pseudorange R' to each satellite by noting the arrival time of the signal. Each of the four R' distances includes an unknown error due to the inaccuracy of the user's inexpensive clock. In this case, there are four unknowns: altitude, latitude, longitude, and clock error. It requires four measurements and four equations to solve these four unknowns.

Figure 11.5 shows the known coordinates of four satellites and the unknown coordinates of the aircraft, for example. The unknown x, y, z represent the longitude,

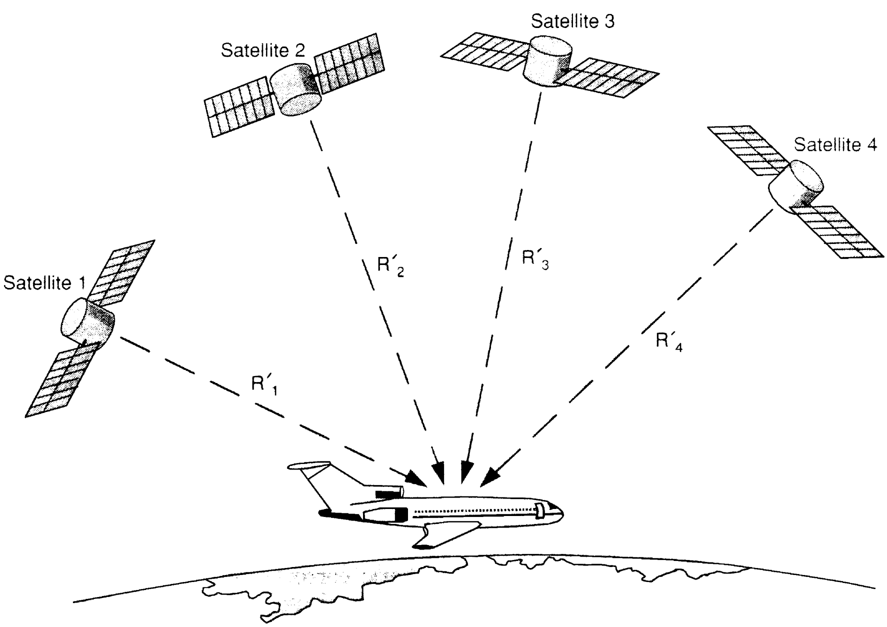


FIGURE 11.4 Determination of the aircraft's position. (From reference [1], with permission from IEEE.)

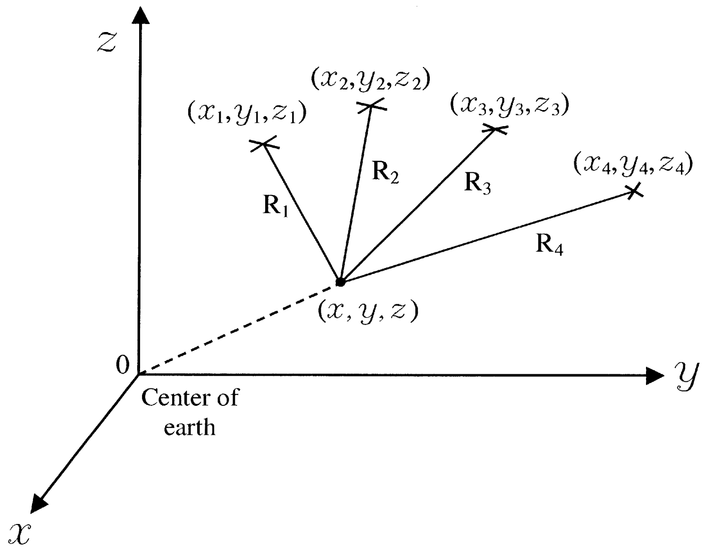


FIGURE 11.5 Coordinates for four satellites and a user.

latitude, and altitude, respectively, measured from the center of the earth. The term ε represents the receiver clock error. Four equations can be set up as follows:

$$[(x_1-x)^2+(y_1-y)^2+(z_1-z)^2]^{1/2}=c(\Delta t_1-\varepsilon)=R_1 \qquad (11.4a)$$

$$[(x_2-x)^2+(y_2-y)^2+(z_2-z)^2]^{1/2}=c(\Delta t_2-\varepsilon)=R_2 \qquad (11.4b)$$

$$[(x_3-x)^2+(y_3-y)^2+(z_3-z)^2]^{1/2}=c(\Delta t_3-\varepsilon)=R_3 \qquad (11.4c)$$

$$[(x_4-x)^2+(y_4-y)^2+(z_4-z)^2]^{1/2}=c(\Delta t_4-\varepsilon)=R_4 \qquad (11.4d)$$

where R_1, R_2, R_3, and R_4 are the exact ranges. The pseudoranges are $R_1'=c\,\Delta t_1$, $R_2'=c\,\Delta t_2$, $R_3'=c\,\Delta t_3$, and $R_4'=c\,\Delta t_4$. The time required for the signal traveling from the satellite to the receiver is Δt.

We have four unknowns (x, y, z, and ε) and four equations. Solving Eqs. (11.4a)–(11.4d) results in the user position information (x, y, z) and ε. Accuracies of 50–100 ft can be accomplished for a commercial user and better than 10 ft for a military user.

11.2 MOTOR VEHICLE AND HIGHWAY APPLICATIONS

One of the biggest and most exciting applications for RF and microwaves is in automobile and highway systems [3–6]. Table 11.2 summarizes these applications. Many of these are collision warning and avoidance systems, blind-spot radar, near-obstacle detectors, autonomous intelligent cruise control, radar speed sensors, optimum speed data, current traffic and parking information, best route information,

TABLE 11.2 Microwave Applications on Motor Vehicles and Highways

I. Motor vehicle applications
Auto navigation aids and global positioning systems
Collision warning radar
Automotive telecommunications
Speed sensing
Antitheft radar or sensor
Blind spot detection
Vehicle identification
Adaptive cruise control
Automatic headway control
Airbag arming
II. Highway and traffic management applications
Highway traffic controls
Highway traffic monitoring
Toll-tag readers
Vehicle detection
Truck position tracking
Intelligent highways
Road guidance and communication
Penetration radar for pavement
Buried-object sensors
Structure inspection

and the Intelligent Vehicle and Highway System (IVHS). One example of highway applications is automatic toll collection. Automatic toll collection uses Automatic Vehicle Identification (AVI) technology, which provides the ability to uniquely identify a vehicle passing through the detection area. As the vehicle passes through the toll station, the toll is deducted electronically from the driver's account. Generally, a tag or transponder located in the vehicle will answer an RF signal from a roadside reader by sending a response that is encoded with specific information about the vehicle or driver. This system is being used to reduce delay time and improve traffic flow.

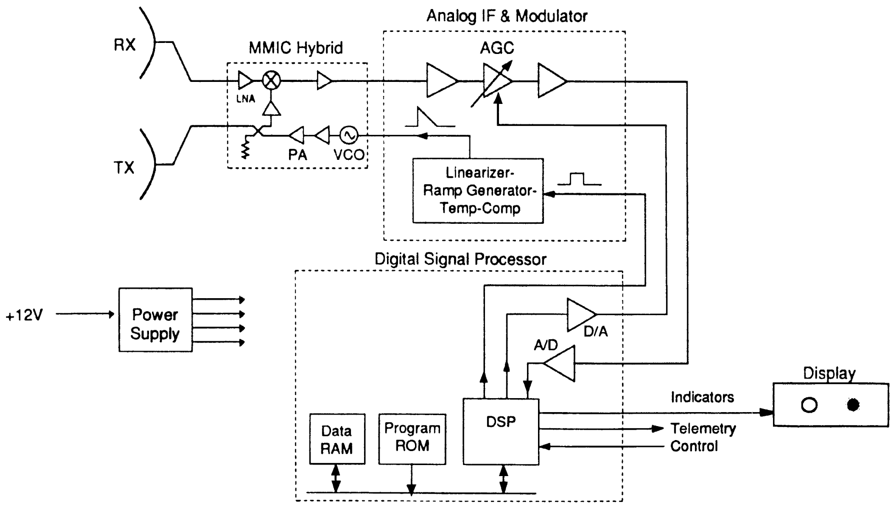
A huge transportation application is IVHS. The IVHS systems are divided into five major areas. Advanced Traveler Information Systems (ATIS) will give navigation information, including how to find services and taking into account current weather and traffic information. Advanced Traffic Management Systems (ATMS) will offer real-time adjustment of traffic control systems, including variable signs to communicate with motorists. Advanced Vehicle Control Systems (AVCS) will identify upcoming obstacles, adjacent vehicles, and so on, to assist in preventing collisions. This is intended to evolve into completely automated highways. Commercial Vehicle Operations (CVO) will offer navigation information tailored to commercial and emergency vehicle needs in order to improve efficiency and safety. Finally, Advanced Public Transit Systems (APTS) will address the mass transit needs of the public. All of these areas rely heavily on microwave data communications that can be broken down into four categories: intravehicle, vehicle to vehicle, vehicle to infrastructure, and infrastructure to infrastructure.

Since the maximum speed in Europe is 130 km/hr, the anticollision radars being developed typically require a maximum target range of around 100 m. Detecting an object at this distance gives nearly 3 s warning so that action can be taken. Anticollision systems should prove to be most beneficial in low-visibility situations, such as fog and rain. Systems operating all over the frequency spectrum are being developed, although the 76–77 GHz band has been very popular for automotive anticollision radars. Pulsed and FM CW systems are in development that would monitor distance, speed, and acceleration of approaching vehicles. European standards allow a 100-MHz bandwidth for FM CW systems and a 500-MHz bandwidth for pulsed systems. Recommended antenna gain is 30–35 dB with an allowed power of 16–20 dBm. Fairly narrow beamwidths (2.5° azimuth, 3.5° elevation) are necessary for anticollision radar so that reflections are received only from objects in front of or behind the vehicle and not from bridges or objects in other lanes. Because of this, higher frequencies are desirable to help keep antenna size small and therefore inconspicuous. Multipath reflections cause these systems to need 6–8 dB higher power than one would expect working in a single-path environment. Figure 11.6 shows an example block diagram for a forward-looking automotive radar (FLAR) [7].

A nonstop tolling system named Pricing and Monitoring Electronically of Automobiles (PAMELA) is currently undergoing testing in the United Kingdom. It is a 5.8-GHz system that utilizes communication between a roadside beacon mounted on an overhead structure and a passive transponder in the vehicle. The roadside beacon utilizes a circularly polarized 4×4 element patch antenna array with a 17-dB gain and a 20° beamwidth. The vehicle transponder uses a 120° beamwidth. This sytem has been tested at speeds up to 50 km/hr with good results. The system is intended to function with speeds up to 160 km/hr.

Automatic toll debiting systems have been allocated to the 5.795–5.805- and 5.805–5.815-GHz bands in Europe. This allows companies either two 10-MHz channels or four 5-MHz channels. Recommended antenna gain is 10–15 dB with an allowed power of 3 dBm. Telepass is such an automatic toll debiting system installed along the Milan–Naples motorway in Italy. Communication is over a 5.72-GHz link. A SMART card is inserted into the vehicle transponder for prepayment or direct deduction from your bank account. Vehicles slow to 50 km/hr for communication, then resume speed. If communication cannot be achieved, the driver is directed to another lane for conventional payment.

Short Range Microwave Links for European Roads (SMILER) is another system for infrastructure to vehicle communications. Transmission occurs at 61 GHz between a roadside beacon and a unit on top of the vehicle. Currently horn antennas are being used on both ends of the link, and the unit is external to the vehicle to reduce attenuation. The system has been tested at speeds up to 145 km/hr with



Parameters	Requirements
Range	2-100 meters
Range Resolution	0.5 meters
Range Rate Resolution	1.5 km/hr
Antenna Beamwidth	3 by 3 degrees, Linear
Antenna Sidelobes	< -30 dB
Modulation Type	FMCW
Modulation Bandwidth	350 MHz
Transmit Power	> 10 mW
S/N Ratio	10 dB
Display	Laptop Computer via RS232
DC Power Supply	12 volts

FIGURE 11.6 Block diagram and specifications of a W-band forward-looking automotive radar system. (From reference [7], with permission from IEEE.)

single-lane discrimination. SMILER logs the speed of the vehicle as well as transmitting information to it.

V-band communication chips developed for defense programs may see direct use in automotive communications either from car to car or from car to roadside. The 63–64-GHz band has been allocated for European automobile transmissions. An MMIC-based, 60-GHz receiver front end was constructed utilizing existing chips.

Navigation systems will likely employ different sources for static and dynamic information. Information such as road maps, gas stations, and hotels/motels can be displayed in the vehicle on color CRTs. Dynamic information such as present location, traffic conditions, and road updates would likely come from roadside communication links or GPS satellites.

11.3 DIRECT BROADCAST SATELLITE SYSTEMS

The direct broadcast satellite (DBS) systems offer a powerful alternative to cable television. The system usually consists of a dish antenna, a feed horn antenna, an MMIC downconverter, and a cable to connect the output of the downconverter to the home receiver/decoder and TV set. For the C-band systems, the dish antenna is big with a diameter of 3 m. The X-band systems use smaller antennas with a diameter of about 3 ft. The new Ku-band system has a small 18-in. dish antenna. The RCA Ku-band digital satellite system (DirecTV) carries more than 150 television channels.

For all DBS systems, a key component is the front-end low-noise downconverter, which converts the high microwave signal to a lower microwave or UHF IF signal for low-loss transmission through the cable [8, 9]. The downconverter can be a MMIC GaAs chip with a typical block diagram shown in Fig. 11.7. Example specifications for a downconverter from ANADIGICS are shown in Table 11.3 [10]. The chip accepts an RF frequency ranging from 10.95 to 11.7 GHz. With an LO frequency of 10 GHz, the IF output frequency is from 950 to 1700 MHz. The system has a typical gain of 35 dB and a noise figure of 6 dB. The local oscillator phase noise is −70 dBc/Hz at 10 kHz offset from the carrier and −100 dBc/Hz at 100 kHz offset from the carrier.

The DBS system is on a fast-growth track. Throughout the United States, Europe, Asia, and the rest of the world, the number of DBS installations has rapidly increased. It could put a serious dent in the cable television business.

11.4 RF IDENTIFICATION SYSTEMS

Radio frequency identification (RFID) was first used in World War II to identify the friendly aircraft. Since then, the use has grown rapidly for a wide variety of applications in asset management, inventory control, security systems, access control, products tracking, assembly-line management, animal tracking, keyless

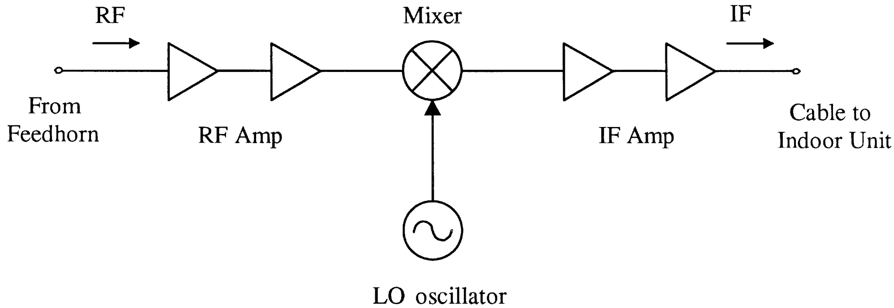


FIGURE 11.7 DBS downconverter block diagram.

TABLE 11.3 Specifications for an ANADIGICS Downconverter

Parameter	Minimum	Typical	Maximum	Units
Conversion gain				
$F_{RF} = 10.95$ GHz	32	35		dB
$F_{RF} = 11.7$ GHz	32	35		dB
SSB noise figure				
$F_{RF} = 10.95$ GHz		6.0	6.5	dB
$F_{RF} = 11.7$ GHz		6.0	6.5	dB
Gain flatness		±1.5	±2	dB
Gain ripple over any 27-MHz band		< 0.25		dB
LO–RF leakage		−25	−10	dBm
LO–IF leakage		−5	0	dBm
LO phase noise				
10 KHz offset		−70	−50	dBc/Hz
100 KHz offset		−100	−70	dBc/Hz
Temperature stability of LO		±1.5		MHz/°C
Image rejection	0	5		dB
Output power at 1 dB gain compression	0	−6		dBm
Output third-order IP	+10	+16		dBm
Power supply current				
I_{DD}	75	120	150	mA
I_{SS}	1	3.5	4	mA
Spurious output in any band			−60	dBm
Input VSWR with respect to 50 Ω over RF band		2 : 1		
Output VSWR with respect to 75 Ω over IF Band		1.5 : 1		

entry, automatic toll debiting, and various transportation uses. In fact, just about anything that needs to be identified could be a candidate for RFID. In most cases, the identification can be accomplished by bar-coded labels and optical readers commonly used in supermarkets or by magnetic identification systems used in libraries. The bar-coded and magnetic systems have the advantage of lower price tags as compared to RFID. However, RFID has applications where other less expensive approaches are ruled out due to harsh environments (where dust, dirt, snow, or smoke are present) or the requirement of precise alignment. The RFID is a noncontacting technique that has a range from a few inches to several hundred feet depending on the technologies used. It does not require a precise alignment between the tag and reader. Tags are generally reusable and can be programmed for different uses.

The RFID tags have been built at many different frequencies from 50 kHz to 10 GHz [11]. The most commonly used frequencies are 50–150 kHz, 260–470 MHz,

TABLE 11.4 Comparison of Systems in Different Frequencies

Parameter	VLF	HF	VHF	UHF	Microwave
Cost	Low	Low	Medium	Medium	High
Interference	Low	High	High	High	Low
Absorption	Low	Low	Medium	Medium	High
Reflection	None	Low	Medium	High	High
Data rate	Low	Medium	Medium	High	High

902–928 MHz, and 2450 MHz. Trade-offs of these frequencies are given in Table 11.4.

The RFID systems can be generally classified as coded or uncoded with examples shown in Fig. 11.8. In the uncoded system example, the reader transmits an interrogating signal and the tag's nonlinear device returns a second-harmonic signal. This system needs only the pass/fail decision without the necessity of the identification of the individual tag. For the coded systems, each tag is assigned an identification code and other information, and the returned signal is modulated to contain the coded information. The reader decodes the information and stores it in the data base. The reply signal may be a reflection or retransmission of the interrogating signal with added modulation, a harmonic of the interrogating signal with added modulation, or a converted output from a mixer with a different frequency (similar to the transponders described in Section 8.7 for satellite communications). The complexity depends on applications and system requirements. For example, the RFID system in air traffic control can be quite complex and the one used for antishoplifting very simple. The complex system normally requires a greater power supply, a sensitive receiver, and the reply signal at a different frequency than the interrogator.

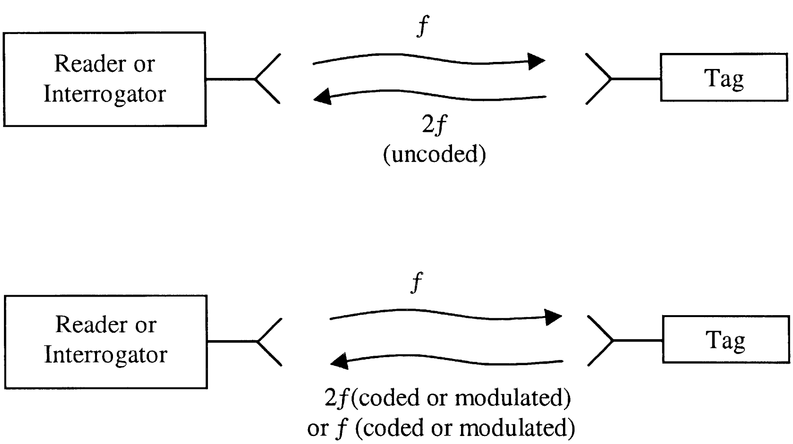


FIGURE 11.8 Simplified RFID systems.

The tags can be classified as active, driven (passive), and passive [12]. The active tag needs a battery; the driven and passive tags do not. The driven tags do need external power, but the power is obtained by rectifying the RF and microwave power from the interrogating signal or by using solar cells. The driven tags could use a diode detector to convert part of the interrogating signal into the DC power, which is used to operate the code generation, modulation, and other electronics.

The low-cost antitheft tags used for stores or libraries are uncoded passive tags. They are usually inexpensive diode frequency doublers that radiate a low-level second harmonic of the interrogating signal. Reception of the harmonic will alert the reader and trigger the alarm.

Numerous variations are possible depending on code complexity, power levels, range of operation, and antenna type. Four basic systems are shown in Fig. 11.9 [12]. The DC power level generated depends on the size of the tag antenna and the RF-to-DC conversion efficiency of the detector diode.

The passive and driven tags are usually operating for short-range applications. The battery-powered active tags can provide a much longer range with more complicated coding. If the size is not a limitation, larger batteries can be used to provide whatever capacity is required. The battery normally can last for several years of operation.

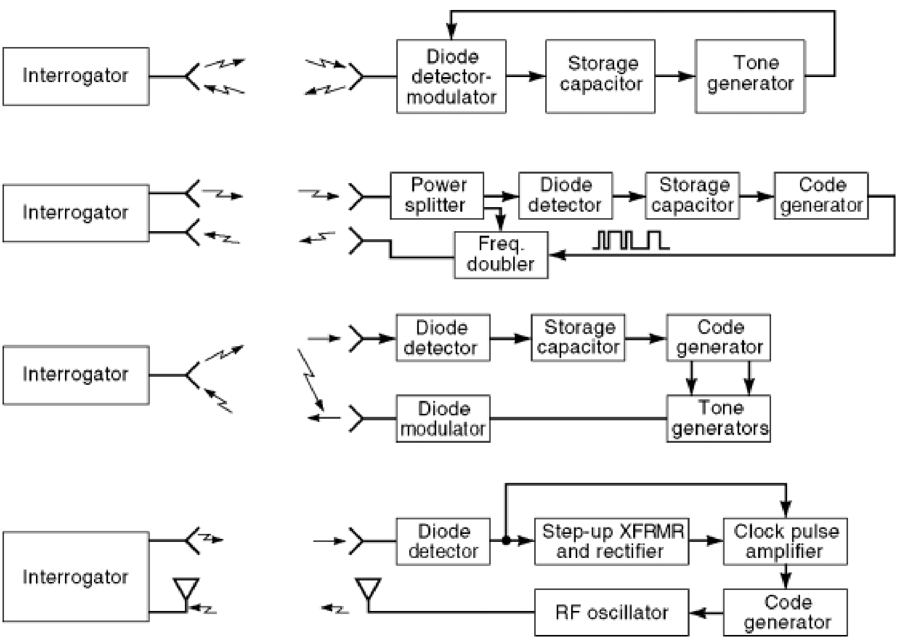


FIGURE 11.9 Four basic types of driven tags. (From reference [12] with permission from *RCA Review.*)

11.5 REMOTE SENSING SYSTEMS AND RADIOMETERS

Radiometry or microwave remote sensing is a technique that provides information about a target from the microwave portion of the blackbody radiation (noise). The radiometer normally is a passive, high-sensitivity (low-noise), narrow-band receiver that is designed to measure this noise power and determine its equivalent brightness temperature.

For an ideal blackbody, in the microwave region and at a temperature T, the noise and energy radiation is

$$P = kTB \tag{11.5}$$

where k is Boltzmann's constant, T is the absolute temperature, and B is the bandwidth.

The blackbody is defined as an idealized material that absorbs all incident energy and reflects none. A blackbody also maintains thermal equilibrium by radiating energy at the same rate as it absorbs energy. A nonideal body will not radiate as much power and will reflect some incident power. The power radiated by a nonideal body can be written as

$$P' = \varepsilon P = \varepsilon kTB = kT_B B \tag{11.6}$$

where ε is the emissivity, which is a measure of radiation of a nonideal body relative to the ideal blackbody's radiation. Note that $0 \leq \varepsilon \leq 1$ with $\varepsilon = 1$ for an ideal blackbody. A brightness temperature is defined as

$$T_B = \varepsilon T \tag{11.7}$$

where T is the physical temperature of the body. Since $0 \leq \varepsilon \leq 1$, a body is always cooler than its actual temperature in radiometry.

All matter above absolute-zero temperature is a source of electromagnetic energy radiation. It absorbs and radiates energy. The energy radiated per unit wavelength per unit volume of the radiator is given by [13]

$$M = \frac{\varepsilon c_1}{\lambda^3 (e^{c_2/\lambda T} - 1)} \tag{11.8}$$

where M = spectral radiant existance, $\mathrm{W/(m^2 \cdot \mu m)}$

ε = emissivity, dimensionless

c_1 = first radiation constant, $3.7413 \times 10^8\ \mathrm{W \cdot (\mu m)^2/m^2}$

λ = radiation wavelength, μm

c_2 = second radiation constant, $1.4388 \times 10^4\,\mu\mathrm{m\ K}$

T = absolute temperature, K

By taking the derivative of Eq. (11.8) with respect to wavelength and setting it equal to zero, one can find the wavelength for the maximum radiation as

$$\lambda_{\max} = \frac{2898}{T} \tag{11.9}$$

where T is in kelvin and $\lambda_{\max}$ in micrometers.

Figure 11.10 shows the radiation as a function of λ for different temperatures. It can be seen that the maximum radiation is in the infrared region (3–15 μm). But the infrared remote sensing has the disadvantage of blockage by clouds or smoke.

A typical block diagram of a radiometer is shown in Fig. 11.11. Assuming that the observed object has a brightness temperature T_B, the antenna will pick up a noise power of kT_BB. The receiver also contributes a noise power of kT_RB. The output power from the detector is [14]

$$V_0 I_0 = G(T_B + T_R)kB \tag{11.10}$$

where G is the overall gain of the radiometer. V_0 and I_0 are the output voltage and current of the detector. Two calibrations are generally required to determine the system constants GkB and GT_RkB. After the calibration, T_B can be measured and determined from Eq. (11.10).

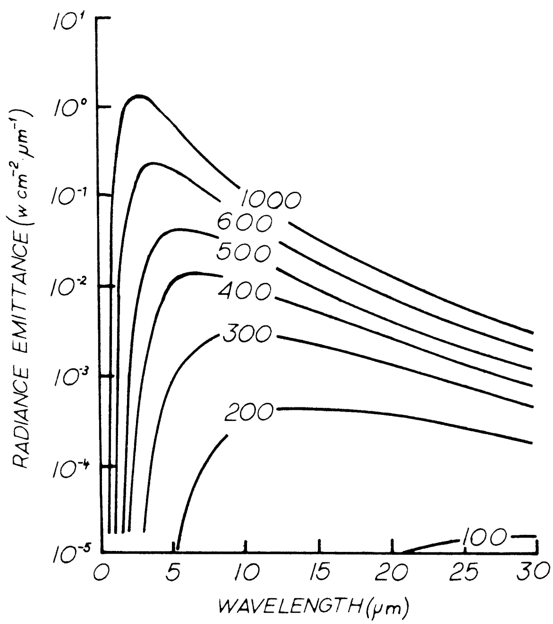


FIGURE 11.10 Radiation curves for different temperatures.

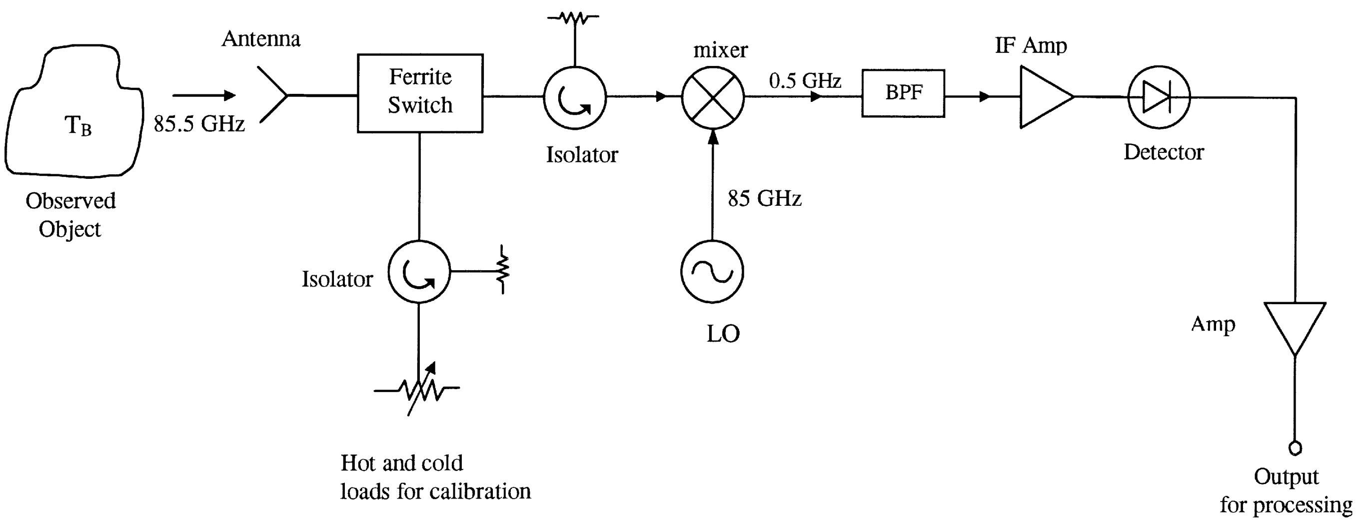


FIGURE 11.11 Radiometer block diagram example.

The major error in this system is due to the gain variation. Such variations occur over a period of 1 s or larger. An error can occur if the measurement is made after the calibrated gain has been changed. The error can be represented by [15]

$$\Delta T_G = (T_B + T_R)\frac{\Delta G}{G} \tag{11.11}$$

As an example, if $T_B = 200$ K, $T_R = 400$ K, and $\Delta G = 0.01G$, then $\Delta T_G = 6$ K. To overcome this error, the Dicke radiometer is used. The Dicke radiometer eliminates this gain variation error by repeatedly calibrating the system at a rapid rate. Figure 11.12 shows a block diagram for the Dicke radiometer. The Dicke switch and low-frequency switch are synchronized. By switching to two positions A and B rapidly, T_{REF} will be varied until V_0 is equal to zero when the outputs from the two positions are equal. At this time, $T_B = T_{\text{REF}}$ and T_B is determined from the control voltage V_c. This method eliminates the errors due to the gain variation and receiver noise.

From the brightness temperature measurements, a map can be constructed because different objects have different brightness temperatures. The target classifications need to be validated by truth ground data. Figure 11.13 shows this procedure.

There are many remote sensing satellites operating at different frequencies, from microwave to millimeter wave and submillimeter wave. For example, the SSMI (Special Sensor Microwave Imager) operates at four different frequencies, 19.35, 22.235, 37, and 85.5 GHz [16]. It was designed to monitor vegetation, deserts, snow, precipitation, surface moisture, and so on. Temperature differences of less than 1 K can be distinguished.

The remote sensing satellites have been used for the following applications:

1. *Monitoring earth environments*: for example, ocean, land surface, water, clouds, wind, weather, forest, vegetation, soil moisture, desert, flood, precipitation, snow, iceberg, pollution, and ozone.
2. *Exploring resources*: for example water, agriculture, fisheries, forestry, and mining.
3. *Transportation applications*: for example, mapping road networks, land and aviation scenarios, analyzing urban growth, and improving aviation and marine services.
4. *Military applications*: for example, surveillance, mapping, weather, and target detection and recognition.

11.6 SURVEILLANCE AND ELECTRONIC WARFARE SYSTEMS

Electronic warfare (EW) is the process of disrupting the electronic performance of a weapon (radar, communication, or weapon guidance). It is a battle for the control of electromagnetic spectrum by deliberate means such as interference, jamming with

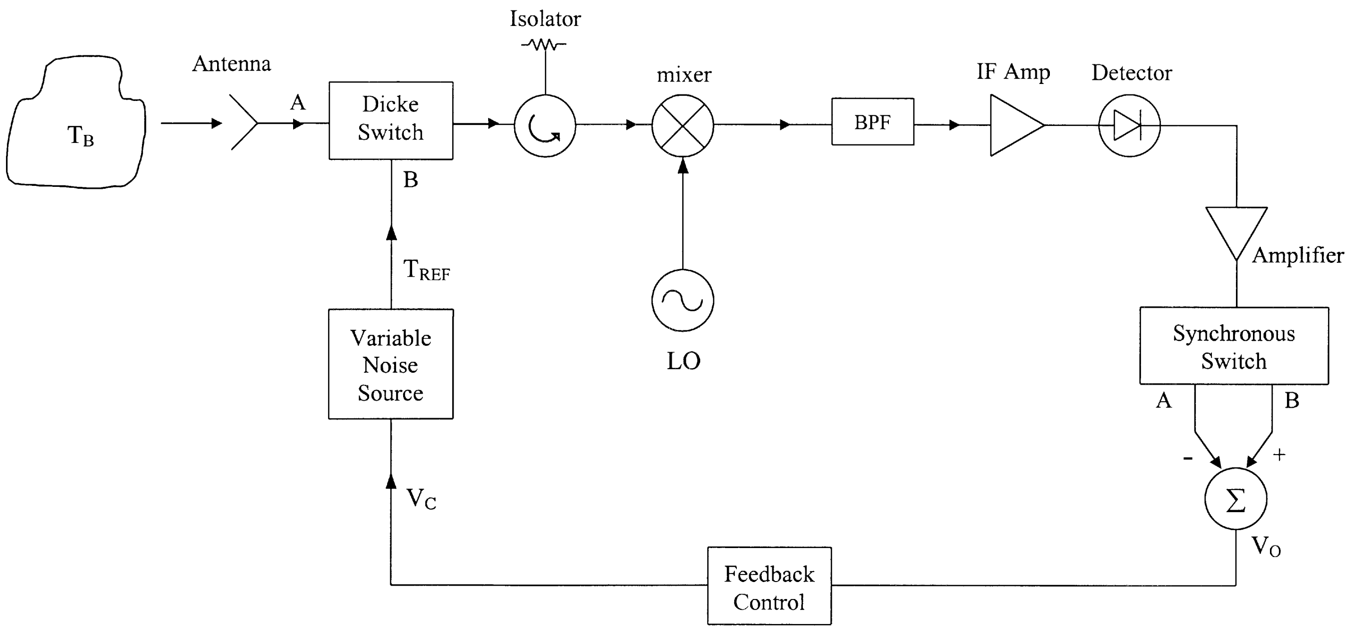


FIGURE 11.12 Dicke radiometer block diagram.

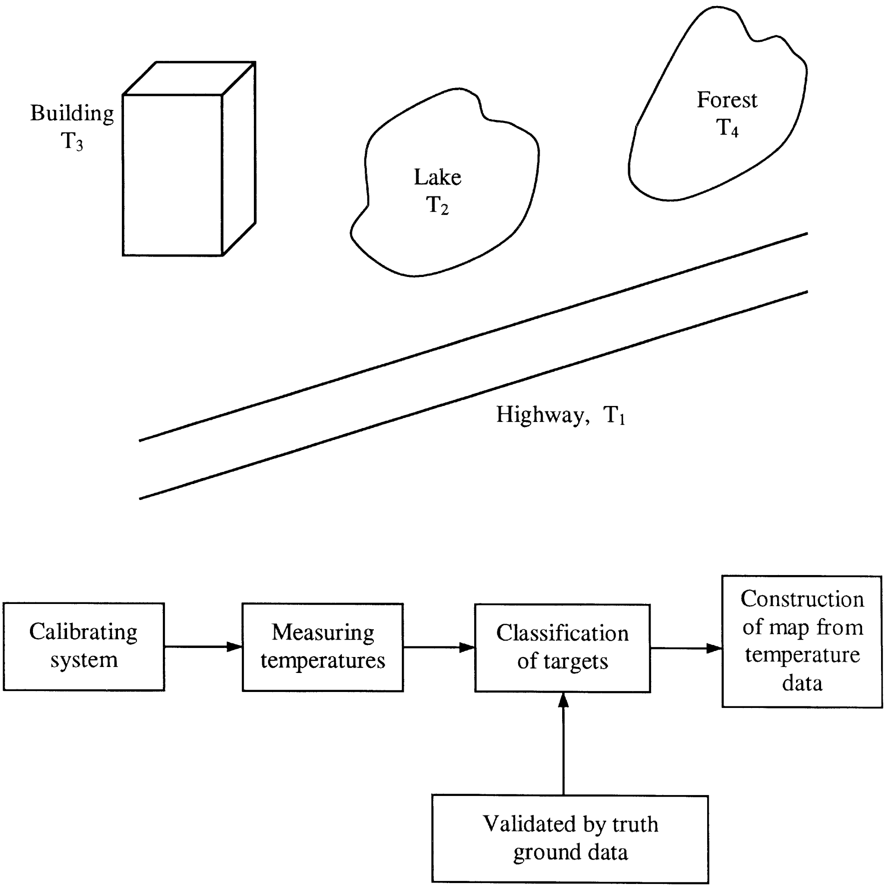


FIGURE 11.13 Procedure for generating remote sensing pictures.

noise, substituting false information (deceptive jamming), and other countermeasures.

Electronic warfare technology can be divided into three major activities: electronic support measure (ESM), electronic countermeasures (ECMs), and electronic counter-countermeasures (ECCMs). Figure 11.14 summarizes these activities [17]. Electronic support measures use a wide-band low-noise receiver to intercept the enemy's communication and radar signals. The intercepted signals will be analyzed to identify the frequency, waveform, and direction. From the intelligence data, the emitter will be identified and recognized. This receiver is also called a surveillance receiver. During peace time, the surveillance is used to monitor military activities around the world. On the battlefield, the findings from ESM will lead to ECM activities. Electronic countermeasures use both passive and active techniques to deceive or confuse the enemy's radar or communication systems. The active ECM system radiates broadband noise (barrage jammers) or deceptive signals (smart

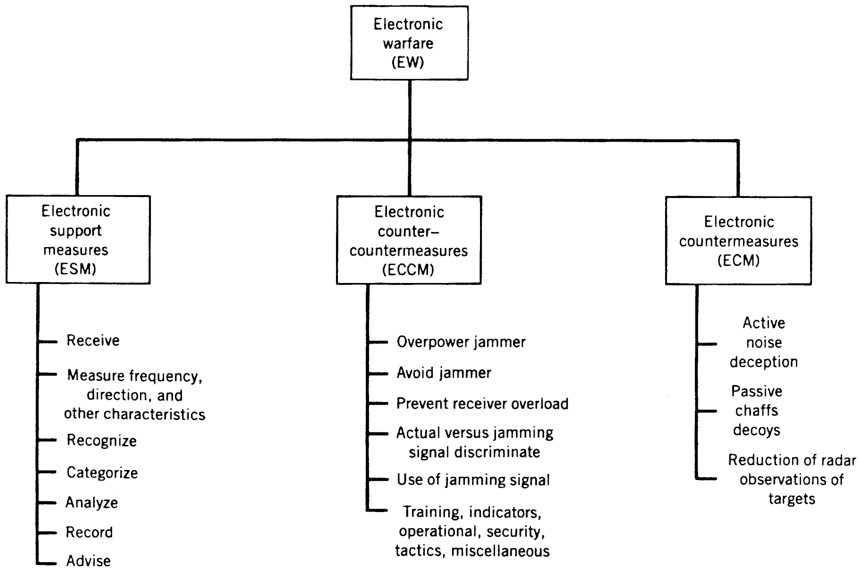


FIGURE 11.14 Modes of electronic warfare [17].

jammers) that confuse or disable the enemy's detection or communication. Passive ECM methods include the use of chaffs or decoys that appear to be targets. A chaff could be a highly reflective material scattered over a large volume to appear as a huge target or multiple targets. The purpose of ECM is to make the enemy's radar and communication systems ineffective. The ECCM actions are taken to ensure the use of the electromagnetic spectrum when the enemy is conducting ECMs. Techniques include designing a receiver with overload protection, using a transmitter with frequency agility, and overpowering a jammer using high-power tubes. The implementation of these techniques requires sophisticated microwave equipment.

11.6.1 ESM System

In the ESM system, the power received from a wide-band receiver is given by the Friis transmission equation, which is similar to the communication system. An example is shown in Fig. 11.15. The received power is

$$P_r = P_t G_t \left(\frac{\lambda_0}{4\pi R} \right)^2 G_r$$
$$= \text{(EIRP) (space or path loss)(receiver antenna gain)} \qquad (11.12)$$

where P_t is the transmitter power from a radar or communication system, G_t is the transmitter gain, λ_0 is the free-space wavelength, R is the range, and G_r is the receiver antenna gain. In many cases, G_t needs to be replaced by G_t^{SL}, which is the

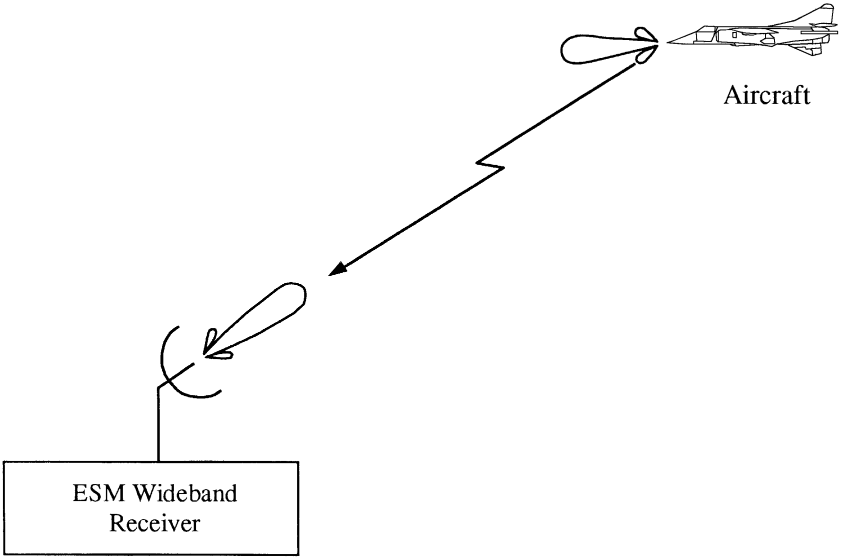


FIGURE 11.15 ESM system.

gain in the sidelobe region since the transmitting signal is not directed to the receiver.

There are many different types of wide-band receivers used for ESM surveillance [17–19]: crystal video receiver, compressive receiver, instantaneous frequency measurement receiver, acousto-optic receiver, and channelized receiver. The crystal video receiver (CVR) consists of a broadband bandpass filter, an RF preamplifier, and a high-sensitivity crystal detector, followed by a logarithmic video amplifier. The approach is low cost and is less complex compared to other methods. The compressive receiver uses a compressive filter when time delay is proportional to the input frequency. By combining with a swept frequency LO signal whose sweep rate $\Delta f/\Delta t$ is the negative of the compressive filter characteristic, a spike output is obtained for a constant input frequency signal. The instantaneous frequency measurement (IFM) receiver uses a frequency discriminator to measure the frequency of the incoming signal. The acousto-optic receiver uses the interaction of monochromatic light with a microwave frequency acoustic beam. The incident light to the acousto-optic medium is diffracted at the Bragg angle, which depends on the wavelength of the incoming signal. The channelized receiver is a superheterodyne version of the crystal video and IFM receivers. It has improved performance but at higher cost and complexity. An example of a channelized receiver is shown in Fig. 11.16 covering 2–18 GHz incoming frequency range [17]. The incoming signal is downconverted to lower IF frequencies. By using a group of decreasing bandwidth filter banks (2 GHz, 200 MHz, and 20 MHz) and the associated downconverters, the signal will appear from one of the detectors. From the detector and the switching information, one can determine the frequency of the incoming signal.

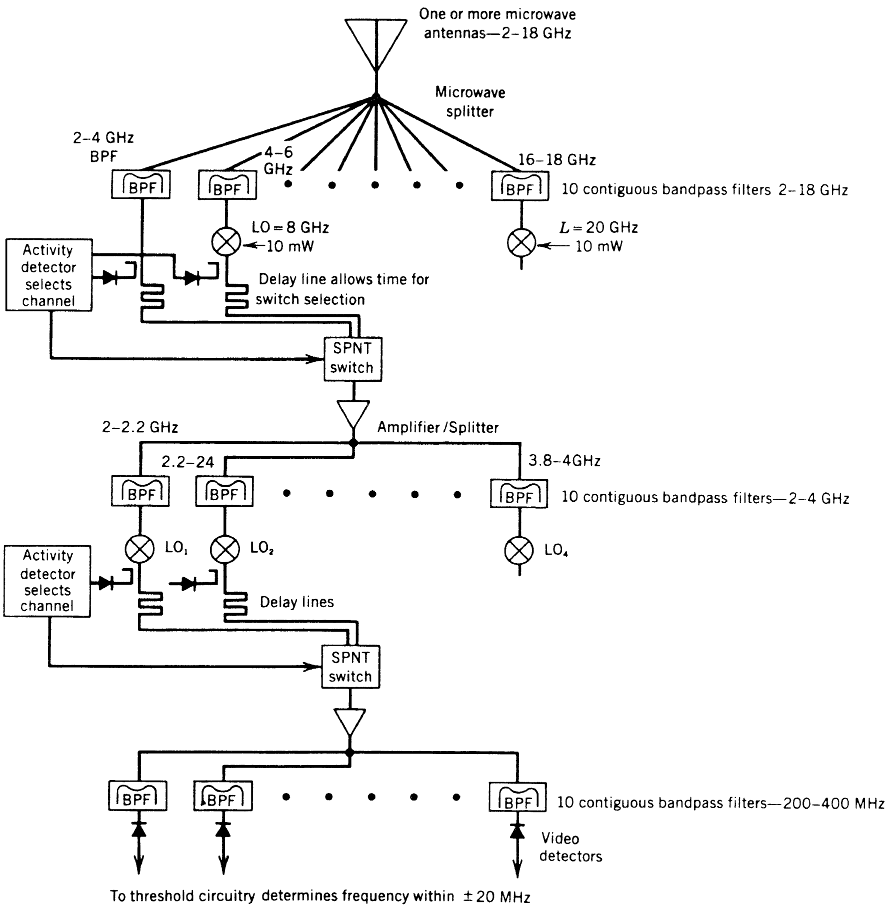


FIGURE 11.16 Channelized receiver [17].

11.6.2 ECM Systems

In ECM systems, the radar equation and Friis transmission equation can be used to describe the jamming scenarios. Two common scenarios are the self-screening jammer (SSJ) and a CW barrage stand-off jammer (SOJ) screening the attack aircraft as shown in Fig. 11.17 [17]. Considering the SSJ case first (Fig. 11.17*a*), the interrogating radar is jammed by a jammer located at the target. The jammer wants to radiate power toward the radar to overwhelm the target return. Effective jamming would require the jammer-to-signal (J/S) ratio received by the radar to exceed 0 dB. From the radar equation (7.12), we have the returned signal from the target given by

$$S = P_r = \frac{P_t G_r^2 \sigma \lambda_0^2}{(4\pi)^3 R^4} \tag{11.13}$$

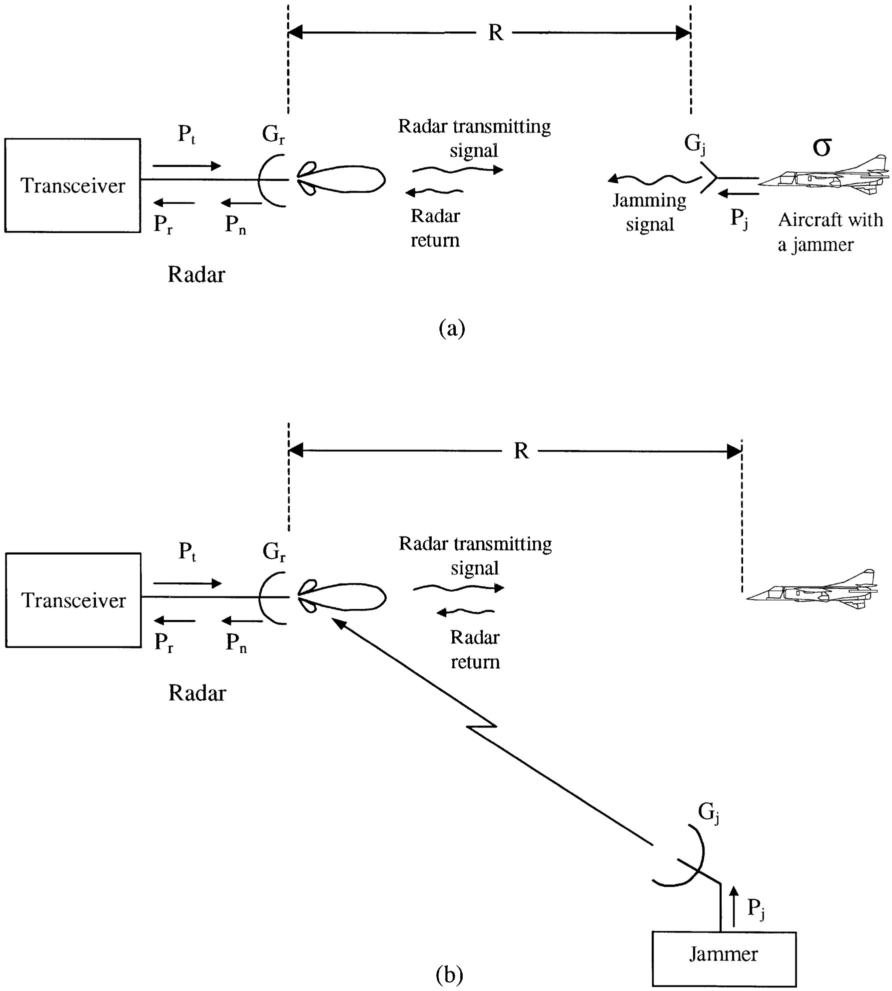


FIGURE 11.17 Two different jamming scenarios: (*a*) self-screening jamming (SSJ) and (*b*) stand-off jamming (SOJ).

The jammer transmits a power level P_j from its antenna with a gain G_j. The jammer has the advantage of one-way loss, and the Friis transmission equation (8.21) is used to calculate the received signal at the radar:

$$J = P_n = P_j G_j G_r \left(\frac{\lambda_0}{4\pi R}\right)^2 \tag{11.14}$$

The J/S ratio can be found by Eqs. (11.13) and (11.14) as

$$\frac{J}{S} = \frac{P_n}{P_r} = \frac{P_j}{P_t} \frac{4\pi R^2 G_j}{G_r \sigma} \tag{11.15}$$

The above equation is valid only when the jammer and radar have the same bandwidth. In practice, the jammer needs to radiate over a broader bandwidth than the radar to be sure that the returned signal is blanked. If B_r is the radar bandwidth and B_j is the jammer bandwidth, the power of the jammer will spread out the bandwidth of B_j. Equation (11.15) is modified to account for the bandwidth effects. We have

$$\frac{J}{S} = \frac{P_n}{P_r} = \frac{P_j}{P_t}\frac{4\pi R^2 G_j}{G_r \sigma}\left(\frac{B_r}{B_j}\right) \tag{11.16}$$

For the stand-off scenario (Fig. 11.17*b*), the jammer is situated on another location other than the target. The radar is aimed at the target, and the jammer is located off the radar's main beam. The jamming signal received by the radar is

$$J = P_n = P_j G_j \cdot G_r^{\mathrm{SL}}\left(\frac{\lambda_0}{4\pi R_j}\right)^2 \tag{11.17}$$

where R_j is the distance between the jammer and the radar and G_r^{SL} is the gain in the sidelobe region of the radar antenna. From Eqs. (11.13) and (11.17), the J/S ratio is

$$\frac{J}{S} = \frac{P_n}{P_r} = \frac{P_j G_j G_r^{\mathrm{SL}}(4\pi)R^4}{P_t G_r^2 \sigma R_j^2} \tag{11.18}$$

If the bandwidths of the radar and jammer are different, Eq. (11.18) becomes

$$\frac{J}{S} = \frac{P_j G_j G_r^{\mathrm{SL}}(4\pi)R^4}{P_t G_r^2 \sigma R_j^2}\left(\frac{B_r}{B_j}\right) \tag{11.19}$$

Example 11.1 A 3-GHz tracking radar has an antenna gain of 40 dB, a transmitter power of 200 kW, and an IF bandwidth of 10 MHz. The target is an aircraft with a radar cross section of 5 m^2 at a distance of 10 km. The aircraft carries an ECM jammer with an output power of 100 W over a 20-MHz bandwidth. The jammer has an antenna gain of 10 dB. Calculate the J/S ratio.

Solution

$B_r = 10\ \text{MHz} = 10^7\ \text{Hz}$	$B_j = 20\ \text{MHz} = 2 \times 10^7\ \text{Hz}$
$G_r = 40\ \text{dB} = 10^4$	$\sigma = 5\ \text{m}^2$
$G_j = 10\ \text{dB} = 10$	$R = 10 \times 10^3\ \text{m}$
$P_t = 200\ \text{kW} = 2 \times 10^5\ \text{W}$	$P_j = 100\ \text{W} = 10^2\ \text{W}$

From Eq. (11.16), the J/S ratio is given as

$$\frac{J}{S} = \frac{P_j}{P_t}\frac{4\pi R^2 G_j}{G_r \sigma}\left(\frac{B_r}{B_j}\right)$$

$$= \frac{10^2 \times 4\pi \times (10 \times 10^3)^2 \times 10}{2 \times 10^5 \times 10^4 \times 5}\left(\frac{10^7}{2 \times 10^7}\right)$$

$$= 62.83 \text{ or } 17.98 \text{ dB}$$

PROBLEMS

11.1 In an active radio navigation system, an aircraft transmits a pulse-modulated signal at f_1. The return pulses at f_2 are delayed by 0.1 msec with a measurement uncertainty of 0.1 μsec. Determine (a) the distance in kilometers between the aircraft and the station and (b) the uncertainty in distance in meters.

11.2 A passive radio navigation system transmits a signal to an aircraft. The signal arrives 1 msec later. What is the distance between the aircraft and the station?

11.3 A ship receives signals from three radio navigation stations, as shown in Fig. P11.3. The coordinates for the ship and the three stations are (x, y), (x_1, y_1), (x_2, y_2), and (x_3, y_3), respectively. The receiver clock error is ε. Derive three equations used to determine (x, y) in terms of the signal travel times and ε.

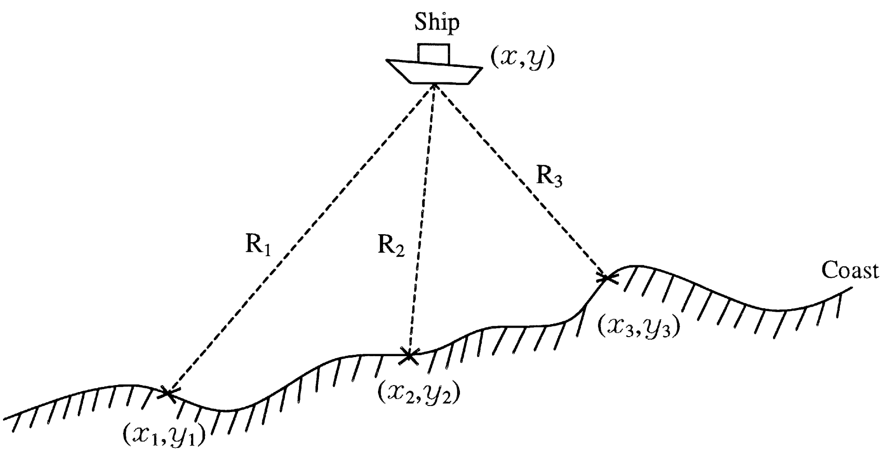


FIGURE P11.3

11.4 The DBS receiver shown in Fig. P11.4 consists of an RF amplifier, a mixer, and an IF amplifier. The RF amplifier has a noise figure of 4 dB and a gain of

15 dB. The mixer has a conversion loss of 6 dB, and the IF amplifier has a gain of 35 dB and a noise figure of 8 dB. Calculate the overall noise figure and gain.

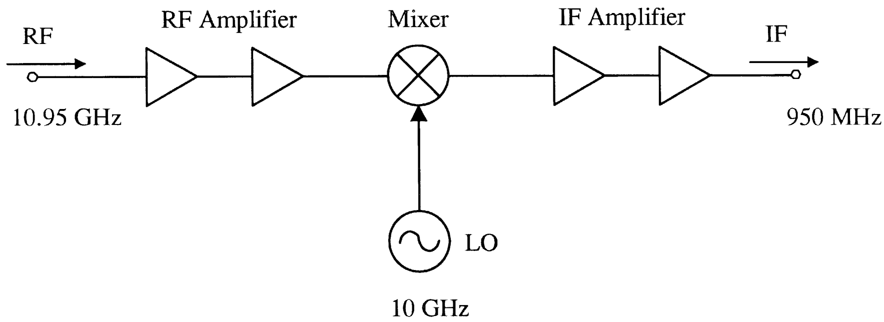


FIGURE P11.4

11.5 The RFID system shown in Fig. P11.5 consists of a reader and a passive tag. The reader transmits a signal at 915 MHz with a power level of 100 mW. The reader antenna has a gain of 10 dB. The tag is located 1 ft away from the reader with an antenna gain of 3 dB. The signal received by the tag is converted to 1830 MHz by a diode frequency doubler. The conversion efficiency is 10%. Assuming that the antenna is in the far-field region, determine the power level P_0 after the conversion. This power is transmitted back to the reader through a tag antenna.

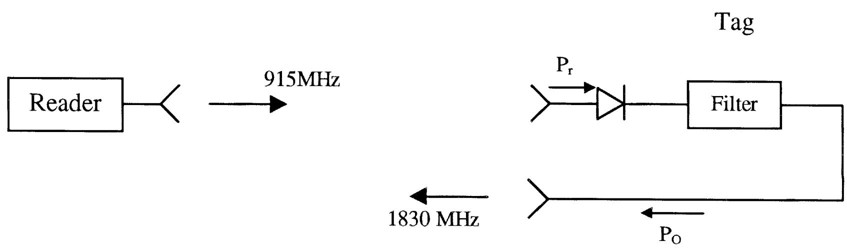


FIGURE P11.5

11.6 A 10.5-GHz police radar detector is used for surveillance. The detector consists of a p–i–n diode as an RF modulator followed by a detector, as shown in Fig. P11.6*a*. The police radar transmits a 10.5-GHz CW signal. Draw the waveform after the p–i–n diode (point A) and the waveform for the output at the detector (point B). The bias to the p–i–n diode is shown in Fig. P11.6*b*, and the pulse repetition rate is in the kilohertz region. Explain how the system works.

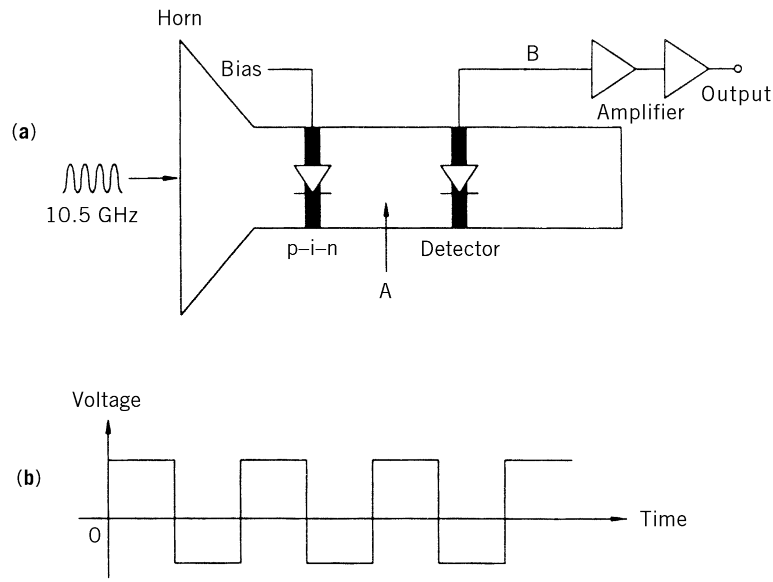


FIGURE P11.6

11.7 A 10-GHz tracking radar has an antenna gain of 30 dB, a transmitting power of 100 kW, and an IF bandwidth of 20 MHz. The target has a cross section of 10 m^2 and carries an ECM jammer with an output power of 100 W over a 30-MHz bandwidth. The jammer has an antenna gain of 10 dB. The target is located at a distance of 5 km from the radar. Calculate the J/S ratio.

11.8 In Problem 11.7, if the same jammer is a stand-off jammer located at a distance of 5 km from the radar, what is the J/S ratio? The radar sidelobe level at the stand-off jammer direction is 20 dB down from the peak level.

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