PART 2

WIRELESS COMMUNICATIONS TECHNOLOGY
Chapter 5

Voice Versus Data

Two types of communications, voice and data, have been traditionally sent over public safety radio systems. Voice communications includes all audio transmissions, which start as voice and end as voice.

Data communications involves the transmission of data from one computer to another, through one or more communications channels (standard telephone lines, radios, etc.). When data are sent over long distances, it is likely that a number of different types of communications channels will be used.

For example, figure 5-1 shows the various communications methods involved in sending data from an agency in California to an agency in Florida.
Voice normally occurs as an analog signal. In other words, the signal may vary continuously over a specific range of values. In figure 5-2, the voltage of the analog signal may take on any value between -10 volts and +10 volts.

![Figure 5-2. Analog Signal](image)

Computers store data electronically. Circuits in the computer can detect the presence or absence of electronic impulses. A bit (binary digit) is the smallest piece of information contained in a data transmission and can only represent one of two values: a zero (0) or a one (1). Combinations of bits are strung together to represent numbers, letters, and other special characters.

Data can also be represented as a digital signal, which can only assume discrete values. For example, in figure 5-3 below, the voltage of the digital signal may only take on the values of either 0 volts (“off” or zero) or +5 volts (“on” or one).

![Figure 5-3. Digital Signal](image)

**Analog Versus Digital**

Voice and data can both be packaged and transmitted using either analog or digital signals. This section discusses the differences between using an analog transmission method and a digital transmission method.
Analog Radio Systems

Analog radio systems continuously transmit radio waves that are usually modulated by a voice. A typical analog voice radio consists of a transmitter and receiver (figure 5-4).

![Figure 5-4. Block Diagram of a Typical Radio System](image)

An analog system may also carry data. However, the data, which are in digital form of binary digits, or bits (i.e., ones and zeros), must first be converted to an analog signal. A modem (modulate/demodulate unit) is used to convert the ones and zeros into two analog tones representing either a one or a zero. When the analog data arrive at the receiver, they are converted back to digital form again using another modem.

Figure 5-5 shows a laptop computer connection through a modem to a typical two-way FM radio. The laptop generates data as ones and zeros that are converted via the modem to analog tones that go into the radio transmitter. Once received, the detected tones pass through a second modem that converts the signal back to digital data and sends them on to another computer for additional processing (e.g., display, printing, query to NCIC).

![Figure 5-5. Block Diagram of an Analog Cellular Phone with a Laptop Computer](image)

Digital Radio Systems

People cannot usually understand digital signals. Our senses are analog oriented and can only respond to continuous signals or impressions. Therefore, we must hear voice transmissions on a loudspeaker or a set of headphones and see visual signals, on either a video monitor or a printer, as words and pictures.
Voice transmissions may be sent over digital radio systems by sampling voice characteristics and then changing the sampled information to ones and zeros to modulate the carrier. This is done using a circuit called a voice coder, or “vocoder.” At the receiver, the process is reversed to convert the digital voice samples back into analog voice.

A diagram of a typical digital voice radio system is shown in figure 5-6.

A digital radio system transmits data directly, by digitally modulating a carrier. One simple method of modulation is to change the carrier frequency by shifting it different amounts for each type of bit. (This is called frequency shift keying, or FSK.) The receiver then receives the signal as a zero or as a one and recreates the original signal.

A simplified digital radio is shown in figure 5-7. The ones and zeros are detected and regenerated at a receiver for use in a computer.

**Transmission Differences**

Analog and digital radio systems have vastly different transmission characteristics. As you move away from an analog radio transmitting site, the signal quality decreases gradually while noise levels increase. The signal becomes increasingly more difficult to understand until it can no longer be heard as anything other than static.

A digital signal has fairly consistent quality as it moves away from the transmitter until it reaches a threshold distance. At this point, the signal quality takes a nose dive and can no longer be understood.
A comparison of the transmission differences between analog and digital signals is shown in figure 5-8.

Encryption

Encryption is a methodology that scrambles a voice or data message to protect its content from unauthorized use, or from those who would use it to the disadvantage of the agency or the public (such as the media during a hostage situation).

Encryption technology is regulated by the federal government and is generally broken into 4 types: Type I is restricted to federal agencies for uses involving national security; Type II is currently not defined; Type III is available for use by local/state government agencies; and Type IV is available for use by the general public.

Older analog radio systems employed encryption systems that chopped voice spectrum into pieces and rearranged or inverted these pieces to make them difficult to understand. The resulting encrypted audio was often high-pitched, sounding like a cartoon character talking. There was no change in system coverage with this technology.

Later digital implementations of encryption converted the analog voice spectrum to a digital waveform and transmitted it with a different modulation. While much more secure than analog inversion systems, the range of these systems was often severely degraded when operating in encrypted mode.
Current digital encryption technology, when applied to digital radio systems such as Project 25, simply adds an encryption algorithm into the digital path. With reference to Figure 5-6, this "encryption box" is added between the Vocoder and the Modulator (for the transmitter) or Demodulator (for the receiver). The signal is already digital and the algorithm simply rearranges the bits so that a standard vocoder (for voice) or terminal (for data) can not regenerate a usable result. Because the system is already digital, the incremental cost to add a high level of encryption is usually low.

Encryption is used by more than just law enforcement agencies. Many fire departments transmit information such as alarm reset codes for businesses and private residences that could be unlawfully intercepted.

However, encryption is only as effective as the management of the "keys" used to protect the information. "Keys" are the data words (usually a group of random numbers or letters) used to control the encryption algorithm. All radios in an encrypted system must be loaded with the same key in order to understand the information being exchanged. These keys must be properly managed so that they do not fall into the possession of unauthorized personnel. They also need to be changed frequently in order to protect information. Given time, an unauthorized person can try many keys and eventually find the proper one to decode a transmission; if keys are not changed frequently, that person then has access to your information. Weekly re-keying with a random key is recommended for most local/state users.

When considering encryption, keep the following important issues in mind:

1. Legal requirements to protect information from eavesdropping. These typically vary by state and are especially important for criminal history information.

2. The time-sensitivity of information to be protected. This is the important property to be considered when determining the level of encryption needed. It is generally only necessary to protect information so that it cannot be used to undermine the operational aspects of an incident. Remember that most information, including actual radio transmissions, is available through the discovery process in court, or by Freedom of Information Act requests.

3. Media impact. The media can be your friend or foe when implementing encryption if they have always been able to monitor your voice radio system. Many agencies find that it is advantageous from the aspect of good media relations to encrypt voice transmissions on tactical channels and leave dispatch channels in "clear" mode.

Finally, all agencies employing more than a few (perhaps 10) encrypted field units on a digital radio system (such as a Project 25 system) should consider purchasing the Over-The-Air-Rekeying (OTAR) option. OTAR allows new keys to be effectively and securely loaded to field units from a central location, with assurance that all authorized units are re-keyed the next time they access the system. The incremental cost to add OTAR when compared with ongoing personnel costs to manually load keys usually makes this a cost-effective addition to an encrypted system.
Chapter 6

Characteristics of Radio Systems

Understanding Radio Terms

Radio technology is full of confusing terms that come straight from a physics book. Sometimes when you ask a radio engineer a question, you even get an answer that is a formula. The authors have tried to simplify the terms as much as possible to allow you to get a good handle on the concepts. The goal in this section is not to turn you into radio experts, but it is hoped that you’ll be able to understand the experts a little better when they talk to you.

Wave

The basic building block of radio communications is the radio wave. Like waves on the ocean, a radio wave is merely a stream of repeating peaks and valleys (figure 6-1).

One big difference between ocean waves and radio waves is that ocean waves are visible, while radio waves are not. People can see how far apart or how high the peaks are on the ocean. Radio waves have those same characteristics; people just cannot see them.
**Wavelength**

The length of a wave is measured from one point to its next corresponding point. In other words, the wavelength could be the distance from one peak to the next peak or from one valley to the next valley and so on, as shown in figure 6-2.

In radio terms, a *short* wavelength would mean that the peaks are relatively close together. A *long* wavelength would mean that the peaks are relatively far apart.

**Cycle**

The entire pattern of the wave, before it begins to repeat itself, is called a cycle. A repeating pattern of cycles that make up a wave is shown in figure 6-3.

**Frequency**

Cycles repeat over time. The fact that they do is the basis for one of the most important terms in radio communications: *frequency*. Frequency is defined as the number of cycles that occur each second.
When they talk about frequency, radio engineers use a shorthand term for “cycles per second,” which they call “Hertz.” (The word Hertz is usually shortened to “Hz” when written.) Both terms mean the same thing. So, if you were told the frequency of the wave was 10 Hertz, you would know that meant 10 cycles per second.

Thousands of radio wave cycles usually repeat themselves each second, so engineers have adopted the practice of writing kilohertz (shortened to KHz), which means 1,000 cycles per second, megahertz (MHz), which means 1 million cycles per second, or gigahertz (GHz), which means 1 billion cycles per second, when they refer to radio frequency. Thus, 10 million cycles per second can also be written as 10 MHz.

Frequency and wavelength are inversely related. In other words, the higher the frequency, the shorter the wavelength, and conversely, the lower the frequency, the longer the wavelength. These relationships are illustrated in figure 6-4. At 300 MHz (300 million cycles per second), the distance between the peaks of the wave is 1 meter. When the frequency is tripled to 900 MHz (900 million cycles per second), the wavelength is reduced to 1/3 meter (1/3 of the previous distance between the peaks).

At extremely high frequencies (above 30 GHz), the distance between the peaks of the wave becomes so small (1 centimeter or less) that a raindrop would not fit between them. In fact, at these extremely high frequencies, it is possible for rainy weather to disrupt the wave and distort or completely block the resulting signal.

**Spectrum and Bands**

The complete range of possible frequencies that are now or could be used for radio communications is called the spectrum. The audible frequency range is usually considered to range from 20 to 18,000 cycles per second or Hertz. For practical purposes, the useful radio spectrum ranges from approximately 30 KHz up to more than 300 GHz.
Radio professionals often discuss frequencies by grouping them into ranges, which are called *bands*. The bands are often referred to by names like HF (high frequency), VHF (very high frequency), UHF (ultra-high frequency), SHF (superhigh frequency), EHF (extremely high frequency), and infrared.

**Public safety bands.** Two of the radio frequency bands are of particular interest to law enforcement agencies installing their own mobile radio systems. These are the VHF and UHF bands, whose ranges are designated as VHF 30 - 300 MHz and UHF 300 - 3,000 MHz.

Specific bands and frequencies used for public safety wireless communications are shown in table 6-1.

<table>
<thead>
<tr>
<th>Public Safety Band Name</th>
<th>Frequencies (MHz)</th>
<th>Channel Separation (KHz)</th>
<th>Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>VHF (low band)</td>
<td>25 - 50</td>
<td>20</td>
<td>Mixed base and mobile</td>
</tr>
<tr>
<td></td>
<td>72 - 76</td>
<td></td>
<td>Mixed base and mobile</td>
</tr>
<tr>
<td>VHF (high band)</td>
<td>150 - 174</td>
<td>15</td>
<td>Mixed base and mobile</td>
</tr>
<tr>
<td>UHF</td>
<td>450 - 512</td>
<td>12.5</td>
<td>Mixed base and mobile</td>
</tr>
<tr>
<td>UHF (700/800/900)</td>
<td>750/800/900</td>
<td>6.25/12.5/25</td>
<td>Mixed base, mobile, and cellular</td>
</tr>
<tr>
<td>2 GHz</td>
<td>2,000</td>
<td>10/20/30 MHz</td>
<td>Personal Communications Services</td>
</tr>
</tbody>
</table>

1 This is the separation most of the time. New equipment below 512 MHz has separations of 12.5 or 15 KHz until 2006, when the separations will be halved again (i.e., in the 150 MHz band, the bandwidth will be 7.5 KHz in 2006).

**Channels**

The Federal Communications Commission (FCC) arbitrarily groups frequencies into categories they call *channels*. When the FCC licenses a channel to you, it specifically identifies the center frequency (sometimes called carrier frequency) for that channel. This central frequency is the main frequency for carrying the information to be transmitted. Thus, the radio information is transmitted over the several frequencies contained within a single channel. The more frequencies in a channel, the greater its width (called *bandwidth*), and the greater the amount of information it can carry.

For example, if a channel were similar to a multilane highway, then the frequencies would be like all the lanes of the highway that travel in the same direction, say northbound (see figure 6-5). The information traveling over the channel is like the cars that travel on the highway. The width of the highway (i.e., the bandwidth) will equal the total width of all the lanes combined. Therefore, the more lanes on the highway,
the more cars that highway can handle. The center lane on the highway would be similar to the center or carrier frequency.

In a similar way, a second channel could be compared to the other side of the highway where all of the lanes travel in a different direction (southbound). A concrete barrier or median strip exists to separate the northbound lanes from the southbound lanes. A similar non-overlap space exists between channels and is called the guard band.

One more note: In our example, the northbound highway has five lanes, while the southbound highway has only three. Like highways, not all channels need be the same width, even if they occur in the same band.

As mentioned before, generally, the wider the bandwidth, the more information may be transmitted. However, with microprocessors and sophisticated software techniques, more information can now be sent
through less bandwidth than was possible just a decade ago (sort of like car pooling). As a result, spectrum efficiency has improved.

**Mobile Radio System Frequencies**

The FCC has assigned frequencies so that there are typically 25 KHz between channels in the UHF band. In other words, a 460 MHz frequency assignment (the center frequency) means that the information transmission falls between 459,987.5 KHz and 460,012.5 KHz (i.e., 12.5 KHz on either side of the center frequency).

In its goal to promote the efficient use of the spectrum, the FCC is changing most of the bandwidths of radio channels below 512 MHz in a process it calls “refarming.” It is presently reducing channel bandwidths in half and will reduce the bandwidths in half again in the year 2006. In other words, the first step is to reduce the channel bandwidth from 30 KHz to 15 KHz, then to 7.5 KHz (or, for a 25 KHz VHF channel bandwidth, to 12.5 KHz, and then to 6.25 KHz).

Frequencies covering TV channels 60–69 have been reallocated from television to private use and public safety use. The nonpublic safety frequencies being reallocated will be auctioned off by the FCC. The 24 MHz of public safety spectrum includes the 764-776 and 794-806 MHz portions of this band. The FCC has required that all systems in this band employ digital modulation. The band has been split into two sections. The voice portion of this spectrum is based on 6.25 KHz channel width building blocks that can be combined up to 25 KHz maximum. The use of conventional equipment using the Project 25 common air interface standard is required on the 64 interoperability voice channels designated in this band. The wideband data portion of this band is built on 50 KHz building blocks that can be combined up to 150 KHz maximum, with an interoperability standard now under development for interoperability data channels.

Spectrum planning in this band is under the auspices of Regional Planning Committees in the same manner as with the earlier 800 MHz NPSPAC band. The FCC formed a Federal Advisory Committee called the National Coordination Committee (NCC) to assist it in developing operational and technical guidelines for this band. Reports and Recommendations from the NCC are available on the FCC website.

**Frequency Selection Considerations**

*Coverage.* In general, the lower the frequency, the better the coverage for a given power level. VHF low band has the best coverage for a given effective radiated power (ERP). This is because the attenuation increases or the signal level decreases as a function of \(1/\text{frequency}^2\). This is why UHF TV stations are permitted to transmit with ERPs of 5 megawatts, compared with VHF TV stations that transmit with 100 to 300 kilowatts. This equalizes the received signals at a far distance.

*Building penetration.* UHF frequencies with shorter wavelengths (typically within the range of 200 MHz to 2000 MHz) have better building penetration through building openings, such as windows and doors, than do VHF frequencies below 200 MHz.
Skip. At VHF low band, stations can experience “skip” (the radio wave reflects from the ionosphere during the height of the sunspot cycle), often causing so much interference that local communications cannot be carried out.

Noise. Natural and manmade noise is worse the lower the frequency. Higher bands experience much less noise interference.

Antenna size. The lower the frequency, the larger the antennas for a given amount of gain. (Reasons for this are discussed in the upcoming section on antennas.)

In summary, selection of the frequency band of operation is dependent upon the desired system characteristics. Table 6-2 summarizes the above-mentioned characteristics.

<table>
<thead>
<tr>
<th>Parameter/Band</th>
<th>Low Band VHF</th>
<th>High Band VHF</th>
<th>UHF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propagation¹</td>
<td>Very good</td>
<td>Good</td>
<td>Poor</td>
</tr>
<tr>
<td>Building penetration²</td>
<td>Poor</td>
<td>Better</td>
<td>Good</td>
</tr>
<tr>
<td>Skip interference</td>
<td>Very susceptible</td>
<td>Little skip</td>
<td>No skip</td>
</tr>
<tr>
<td>Manmade noise</td>
<td>High noise</td>
<td>Less noise</td>
<td>Lowest noise</td>
</tr>
<tr>
<td>Antenna size³</td>
<td>Large</td>
<td>Smaller</td>
<td>Smallest</td>
</tr>
</tbody>
</table>

¹ For a given ERP (signal attenuation is proportional to 1/f²).
² For a dense (concrete) building with windows.
³ For a given amount of antenna gain.

Transmitters and Receivers

Base, mobiles, and handheld radios consist of components called transmitters and receivers. In most cases, some circuitry is used for both transmitting and receiving, so a radio is said to be a transceiver.

Transmitters

A transmitter generates a radio wave or signal. A diagram of a simple transmitter is shown in figure 6-6.

The frequency generating component is called an oscillator. Frequency multipliers multiply the frequency up to the final output frequency. A power amplifier increases the power of the signal to obtain the necessary power output to the antenna.
The output frequency is a continuous wave (CW) called a carrier. Intelligence is added to the transmitter by varying the amplitude of the carrier (amplitude modulation or AM) or by varying the frequency of the carrier (frequency or phase modulation or FM). Figure 6-7 shows the difference between amplitude and frequency modulation. The most noticeable user difference between AM and FM modulation is that FM is less susceptible to interference from RF noise.

**Receivers**

The receiver is the opposite of the transmitter. It receives the modulated carrier, processes it, and sends it to a detector section, which strips off the modulation signal from the carrier to restore the original intelligence. A diagram for a simple receiver is shown in figure 6-8.
Radio systems are generally designed for AM or FM. Voice transmission is produced using a microphone at the input of the transmitter and a loud speaker at the output of the receiver. The signals are usually analog, or continuous, signals.

Data are transmitted using binary signals. One simple method of transmitting a binary signal uses frequency shift keying (FSK). A zero is represented by transmitting a particular carrier frequency, and a one is represented by shifting the carrier frequency to a different frequency (usually with less than 1,000 Hz difference). The receiver interprets the ones and zeroes and reconstructs the binary data stream.

This is just one simple scheme for transmitting data. Most of today’s systems use much more complex methods to maximize spectrum efficiency.

As stated elsewhere in this book, human beings cannot directly interpret most digital signals. People live in an analog world, one with continuous audio frequency loud speakers, printers, television, or computer screens. The exception to this is the use of Morse Code, which consists of ones and zeros. Skillful Morse Code operators can interpret the dots and dashes in their heads into letters and numbers. For digital radio, however, a digital-to-analog converter is necessary to communicate with human beings.

Note that figure 6-8 is greatly simplified. All communications receivers used in dispatch-type communications have squelch circuits before the audio circuits, which keeps the output off when there is no signal (so that you do not have to listen to noise) and passes the detected signal through when the correctly coded signal is received. Several different types of squelch are used. Commonly used squelch schemes are continuous tone-coded squelch system (CTCSS) and the continuous digital-coded squelch system (CDCSS).
Antennas

An antenna allows a radio transmitter to send energy into space and allows a receiver to pick up energy from space. Generally, the higher an antenna is above the ground, the larger the coverage of the radio signal.

The fundamental antenna is the dipole, which consists of a wire or rigid metal rod. A dipole’s length is set to be approximately one-half the wavelength of the carrier frequency. Thus, a 300 MHz carrier, with a wavelength of 1 meter, would need to use a dipole that is ½ meter long. Similarly, the dipole for a 900-MHz carrier, whose wavelength is 1/3 meter, would be 1/6 meter long (approximately 6\(\text{inches}\)).

Assuming the wire is vertical, the three-dimensional radiation pattern is omnidirectional around the wire in the horizontal plane and is donut shaped in the vertical plane, as shown in figure 6-9. (Omnidirectional means that the same amount of radiation can be measured the entire way around, at any given cross-section of the donut.)

If the antenna is vertical to the earth’s surface, its electric field will be vertical, and the antenna is said to have vertical polarization. If the antenna is horizontal and the electric field is parallel to the earth’s surface, the polarization is horizontal. Almost all mobile operations use vertical polarization.

Antenna Gain

Antennas are the transmitting and receiving elements of a radio system. Gain is the focusing of the antenna’s radio frequency (RF) electromagnetic energy toward certain directions. By focusing the energy from or to a dipole antenna in a particular direction, you can increase the effective transmitted power outward towards that direction plus increase the received signal strength from that direction. This is important for two reasons: 1) you may be able to use less power to transmit a signal for the same signal
level at a receiving site; and 2) interfering signals from other directions will decrease in level causing less radio frequency interference for you.

Suppose an antenna that radiates equally in all directions (an isotropic radiator) were represented by a perfectly round air-filled balloon with air as energy, then the energy per unit area (in watts/cm$^2$) on the surface of the sphere would be equal anywhere on the sphere.

We can, however, manufacture a “donut radiator” by feeding energy into a half-wave dipole antenna with a resulting radiation pattern like the one shown in figure 6-9. (Note that only the elevation (vertical) pattern is increased; the azimuth (horizontal plane) pattern is a circle.)

If you were to grab the center of the spherical “isotropic balloon” and squeeze it in the middle so that you had a barbell with equal spherical balloons on each end, a cut through the middle would look like a donut without the hole, similar to the vertical pattern of the dipole shown in figure 6-9. The same watts of energy as in the original sphere (air in our analogy) are now concentrated in the two barbell ends. In addition, the length from the center of the donut to the furthest point on the spheres is now increased, i.e., the original energy is now focused in the two spheres. This increase in length compared to the radius of the original balloon is the “gain” over the isotropic radiator. (The increase in this amplitude over the original balloon radius is 1.64 times, or 2.15 dBi.)

Next, if our hypothetical balloon is squeezed down further, the barbells go out further and the maximum gain in the elevation direction increases (total gain increases). This might occur when two dipoles are fed in phase so the gain is now 3 dBi (or 3 dB greater than that of a dipole), as seen in figure 6-10. Note that in the horizontal direction the pattern is still a circle, although its diameter (3 dBi gain) is twice that of the dipole.

One way to achieve this type of gain is to stack dipoles end to end with some vertical separation between them. This type of antenna is called a colinear gain antenna. As the gain is increased in the elevation pattern, the vertical angle of the beam is reduced. Since the phase of the RF energy into each dipole is not perfect, “side lobes” are developed, as seen in the left side of figure 6-10. The side lobe amplitudes are much less than that of the main lobe. The beam width of the main lobe is defined as the angle between the half power points.

Both isotropic and dipole antennas are used as references for the gain of other antennas. That is, the maximum radiation of an actual focused antenna is compared with that of either an isotropic radiator or a dipole antenna. (Isotropic radiators are generally used for frequencies of 1 GHz or above.) If the reference
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is an isotropic radiator antenna, the decibel measurements are designated as dBi. If the reference is a dipole antenna, the decibel measurements are given in dBd. The gain of the dipole is related to the gain of the isotropic radiator as 2.15 dB.\(^1\) In general, the larger the aperture or the length of an antenna for one frequency, the higher the gain and the smaller the beam width.

Because the vertical beam width is narrowed as a base station’s antenna gain is increased, it is necessary to make sure that the main beam will hit the receiving station antenna. If there are large differences in elevation between transmitting and receiving antennas, there is a possibility of missing them. Base or repeater stations that are placed on very tall buildings or on mountaintops often are designed with a “downtilt” on their patterns to make sure that the maximum radiation hits close-in mobile units.

Gain is important because of its relationship to RF power requirements. For example, if the gain at a base station is doubled in the direction of a mobile, the mobile receiver will receive twice the signal strength power. Similarly, a mobile transmitting towards the base station will have twice the signal strength at the base station. Plus, potential co-channel interfering signals coming from other directions will be lessened with respect to the desired signal.

To summarize, by increasing the gain (or directivity) of an antenna in a two-way radio circuit, you may save money by buying a less powerful transmitter, achieve higher received signal levels from stations in the gain direction, and discriminate against signals on the frequency from other directions.

Types of Antennas

**Base station antennas.** Most base station antennas are omnidirectional in the horizontal plane (azimuth) so that mobile and portable radios may communicate with a base station from any direction. To increase the transmitter and receiver directivity, many base stations use colinear arrays of dipoles for up to 6-decibel gain at VHF stations and up to 12-decibel gain for UHF stations.

**Directional antennas.** If you need to direct the RF energy in one direction and do not need an omnidirectional pattern in the horizontal plane, an antenna may be constructed to shape the pattern toward the single direction. Some of these kinds of antennas are corner reflectors (see figure 6-11), Yagi antennas (see figure 6-12) and parabolic dishes. The patterns in both the horizontal and vertical planes are focused.

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1 Gain = 10\[\log_{10}(P/P_{REF})\], where \(P\) = the maximum power density of a given antenna and \(P_{REF}\) is the maximum power density of either the isotropic radiator or the dipole.
and increase the gain considerably over an omnidirectional dipole.  (Photographs courtesy of Decibel Products, Dallas, TX.)

Mobile antennas. The simplest mobile antenna is a quarter-wave whip antenna. It consists of a single vertical element, approximately 1/4 wavelength long, mounted onto the metal roof of an automobile, and is called a monopole.

The roof acts as a “ground plane” reflector so that the antenna radiation pattern emulates a dipole antenna.

At VHF low band (50 MHz), a quarter wave monopole antenna is about 5 feet long. As the frequency is increased, the length of a monopole antenna is reduced. At 850 MHz, a monopole is only 3.5 inches long.

Portable antennas. Portable radios usually use helically wound or rod antennas attached to the radio. These are usually less efficient than base or mobile antennas. There are also times when your body is between the portable and the base with which it is communicating, causing a decrease in signal. In addition, the height of the portable antenna (belt mounted versus a lapel-mounted speaker-microphone antenna) can make a significant difference in radio coverage. All of these characteristics must be accounted for in designing a system.
Smart antennas. A major development has occurred in the design of "smart antenna arrays" which are able to adjust to their environment so that they enhance desired received signals while discriminating against interference from undesired signals. The antennas are made of a large number of antenna elements each of which are controlled using computer technology in near real time.

An example of a smart antenna is shown in figure 6-13. The main lobes of the antenna are placed directly on the desired signals while nulls are placed at the angle of interfering signals. Each element of the antenna is "tuned" so the composite beam is adjusted to maximize desired signals and minimize undesired interfering signals.

Our human ears work in a similar way at a noisy party. Even though there are several conversations occurring simultaneously, we are able to distinguish between them and focus on only one. Usually we do this by turning towards the desired conversation and concentrating our listening efforts toward the mouth of the desired speaker while “tuning out” the other undesired conversations.

Smart antennas adapt themselves automatically toward the direction of incoming desired signals via digital signal processing (DSP). With DSP, a series of microprocessors changes the phase and amplitude of the elements to focus the antenna pattern in the desired directions while discriminating against interfering signals. The most sophisticated antenna arrays are able to adjust to many different desired signals via space division multiple access (SDMA) so as to process the antenna lobes to accommodate the signals simultaneously.
Although smart antennas are quite costly, the economical trade-off is increasing the capacity of antenna systems to support an increased number of users.

**Effective Radiated Power (ERP)**

Effective Radiated Power, or ERP, is a term used in land mobile radio to indicate the “effective” power radiating from the antenna. ERP in decibels equals the transmitter power output into the transmission line, less the losses in the transmission system (including that of the transmission line, filters, couplers, etc.) plus the gain of the antenna in dBi. It is expressed as:

$$ ERP = P_{IN} - L + G_{ANT} $$

- $ERP$ = Effective radiated power in decibels above one watt
- $P_{IN}$ = Power output from the transmitter in decibels above one watt
- $L$ = All transmission losses in decibels
- $G_{ANT}$ = Antenna gain in decibels above a dipole reference

An example of this is a transmitter with an output power of 100 watts, a coaxial cable with a loss of 2 dB, a combiner loss of 1 dB (total loss of 3 dB), and an antenna with a gain of 6 dBi. The resulting ERP would be calculated as follows:

- $P_{IN}$ = 20 dBW
- $L$ = -3 dB
- $G_{ANT}$ = 6 dBi

$$ ERP = 23 \text{ dBW} $$

When this is converted from dBW to watts, the effective radiated power is 200 watts. One might ask: “How can we have an ERP of 200 watts when the transmitter only puts out 100 watts into the coaxial cable?” There is conservation of power. No physics law has been broken.

ERP is a fictitious number indicating the effectiveness of a transmission as compared to that of a transmitter connected to a dipole with no transmission losses. There is a real point to it. To the receiver listening to this transmission, the transmission will be 3 dB stronger than it would if it came from the same transmitter using a cable with no loss and a dipole antenna.

**Interference**

With the advent of cellular, PCS, specialized mobile radio (SMR) and enhanced specialized mobile radio (ESMR) systems, many new antenna installations must be made throughout the country. To minimize the number of new antenna sites (and associated towers), installations with a multitude of radios combined on a few antennas are becoming more prevalent.

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2 Watts in dBW = 10 logP, where P is in watts. To get the power in watts, we divide dBW by 10 and raise the answer to that power: Power in Watts = 10 \text{^{power in dBW/10}}. 

-55-
As the number of radios and antennas is increased at a site, the interference potential of generating and/or receiving spurious signals is increased. Therefore, filters and isolators (discussed in the next section) must be added to the antenna circuits. Usually, the last station to build at the site causes the interference and is responsible for the additional filtering equipment. Some sites have full-time managers who screen an applicant’s plans to anticipate any interference potential.

Interference may be predicted using a software program by inputting the transmitted signal frequencies and bandwidths and the receiver frequencies and bandwidths. This allows you to determine the intermodulation product frequencies and harmonics that might be generated externally or internally in the equipment. Knowing what may be expected allows you to take preventive action. Some types of filters used are discussed in the duplexer, combiners, and multicouplers sections of this book.

**Radiation**

A potential problem of exposure to harmful radiation exists around transmitting antennas. Service personnel in the vicinity of a tower or climbing a tower could be exposed to harmful radiation. It may be necessary to reduce power or shut down transmitters before climbing a tower. Wearable exposure alarms are available to warn of excessive radiation from Narda Microwave, a division of Lockheed Martin.

The radiation danger is highest when there are high-power broadcast stations at common sites. Radiation exposure requirements for the public are less than for personnel associated with the site (see table 9-1 in chapter 9). To help prevent public exposure, security fences usually are constructed around towers, and the fences are posted with “Hazardous RF” signs.

**Local Regulations Controlling Antennas**

Most cities have zoning ordinances that control the use of land for radio sites. These usually include maximum tower heights and setbacks, as well as the antenna types and radiation characteristics. Usually an application for a radio site is prepared by an applicant and submitted to the zoning board for processing and a recommendation. County commissioners or city council members have the final approval. Members of the public often have the opportunity to voice their opinions regarding the aesthetics and requested use of the site before approval. It is not unusual for a government entity to add stipulations for disguising a tower and antenna. Recent examples include requiring a tower to look like a tree and using a church steeple to house an antenna.

**Radio Coverage**

One of the most important characteristics of a radio system is its coverage. That is, it is important to know exactly where the base or repeater station signals may be received by mobile or handheld radios and exactly where mobile or handheld radio stations may be heard by a base or repeater station.

All parameters must be placed into one of several computer models (called propagation models) to get a reasonably accurate output. These include transmitter power out, transmission line losses, antenna gain and
directivity, foliage losses, building losses (if required), receiver sensitivity, and antenna and transmission line characteristics.

Figure 6-14 shows a typical coverage pattern for a base station (the cross hatched area outlined in black). Notice that there are some holes in the main contour (white areas within the cross hatched area) where signals are not heard, and there are some places (hills) outside of the main contour where there is reception.

Figure 6-14. Sample Coverage Map (courtesy Hartech, Inc.)
Mobile and handheld radios have different characteristics than base stations due to their lower power and to poorer antenna efficiency. Coverage patterns should be made for each kind of radio used in a system so that you know exactly where to expect coverage. If you don’t know that an officer’s portable radio transmission will not be heard at a repeater, it could put the officer’s life in jeopardy.

Coverage should always be verified by running actual tests after a system is constructed. There are testing procedures available from some of the larger system suppliers. These include the use of vehicular calibrated receiver systems, which measure the station signal strengths versus location at points along a predetermined route. Standards are being developed by a Telecommunications Industry Association (TIA) committee consisting of industry and user representatives.

**Duplexers, Combiners, Multicouplers**

Duplexers, combiners, and multicouplers are components that make it possible to connect multiple transmitters and receivers to antennas. These important filtering and isolating components are used in a radio system to optimize its operation and minimize interference with itself as well as other systems.

A single repeater, consisting of a transmitter and a receiver operating on different frequencies, is most often connected to a common antenna. If the transmitter energy gets into the receiver, it can burn out the front-end components or cause severe interference in the receiver and, as a result, in your overall system.

You can use two antennas, one above the other, but this configuration may still not provide enough isolation. Therefore, a duplexer may be used to increase the isolation and to keep the transmission from interfering with received signals.

**Duplexers**

To shield the receiver from the transmitter, cavity filters are often added in the transmitter and receiver transmission lines to form a circuit called a duplexer. There are several configurations.

One method of duplexing is by placing a “pass” filter in the transmitting line and a “reject” filter in the receiving line with both filters tuned to the transmitter frequency, as shown in figure 6-15. When the appropriate isolating components are selected, the receiver does not experience interference from the transmitter. A typical duplexer is pictured in figure 6-16.
Combiners

When trunked radio systems are used with a multitude of transmitters connected to an antenna, a circuit element called a combiner is used to combine the output signals. The combiner (shown in figure 6-17) allows the transmitter outputs to be coupled together, sending the output power of each transmitter to the antenna with minimal loss. A typical transmitter combiner is pictured in figure 6-18 (photos in figure 6-16 and 6-18, courtesy of TX RX Systems, Inc.).
An additional element may be used in the circuit between each transmitter and the combiner to increase isolation to the other transmitter outputs. Such an element is called an isolator, as shown in figure 6-19.

If there is inadequate isolation, the mixing of the transmitted signals can cause the generation of additional frequencies called intermodulation products, or IM products, which may cause interference to nearby receivers.
Multicouplers

A device similar to a combiner, called a *multicoupler*, is used to connect a multitude of receivers to a single antenna. Usually, a multicoupler contains an amplifier that covers all the receiving frequencies and then splits and sends each signal to its particular receiver, as shown in figure 6-20.

![Figure 6-20. Receiver Multicoupler](image)

Multiple Access Systems

Several cellular radio systems are used to improve spectrum efficiency, allowing more users to employ a channel or frequency band. The primary technologies used today are frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA). Public safety radio systems primarily use FDMA and TDMA technologies. To better illustrate these technologies, the examples below describe their implementation by the cellular telephone industry.

Frequency Division Multiple Access (FDMA)

The original cellular radio channels were 30 KHz wide and accommodated one voice signal subscriber. As the number of subscribers increased, some cellular radio companies opted to divide the 30 KHz channels into three 10 KHz channels, which would allow a 3:1 increase in subscribers, as shown in figure 6-21. The process is called frequency division.
Multiple access is accomplished by the cellular radio system control computer having the ability to assign each of the channels to different subscribers. When one subscriber has completed a call or moves into a new cell, the channel may be reassigned to another subscriber.

**Time Division Multiple Access (TDMA)**

Another scheme used by cellular companies is to take the same 30 KHz channel, but instead of dividing it into three narrower channels, it is set up for transmission in three time periods so that three subscribers still use the total 30 KHz; now each subscriber would talk for one-third of the time, thus increasing the number of users by 3:1. By allowing each subscriber to talk for a few milliseconds in rotation, three conversations now take place within the same 30 KHz channel. See figure 6-22.

For time division transmission to work, the voice signal must be digitized by a vocoder (voice coder) and each digitized signal is sent in sequence over the 30 KHz spectrum. The subscriber’s phone must be perfectly synchronized with the transmission so that it only decodes the desired subscriber’s signal in its vocoder. Cell phone and PCS companies have found that by using TDMA, up to eight subscribers may use the same 30 KHz spectrum. Multiple access is accomplished in the same manner as in FDMA above.

Group of special mobile (GSM), which was developed in Europe and is being used by a number of U.S. companies, provides TDMA transmission with 200 KHz wide channels in the 2 GHz band.

**Code Division Multiple Access (CDMA)**

CDMA is a digital modulation that uses spectrum spreading techniques and is more complex than either FDMA or TDMA. The transmission spectrum is always much wider than that required for a single transmission, allowing many simultaneous transmissions to be interspersed within the same bandwidth.
Two types of systems are used: frequency hopping and direct sequence. Both systems use vocoders to digitize the signal.

**Frequency hopping.** The frequency hopping concept is easy to visualize. The transmitter changes frequency every few milliseconds in a prescribed manner as it transmits information. A perfectly synchronized receiver follows the frequency change sequences of the transmitter from one frequency to another to receive the information.

By having as many different frequency changing sequences as there are radios in a given area, many conversations may occur at the same time over the same spectrum. When two transmitter signals collide on the same frequency, the receiving phone transmits a message that it was not received and the original information is resent.

**Direct sequence.** In the direct sequence CDMA, the transmitted digital signals are coded by a “spreading algorithm” in each transmitter. Each receiver has a decoder that decipher the spread signal and recovers the voice. By using several different spreading codes within each algorithm, this system accommodates many different users at the same time.

### Packaging Data

Packet radio is a heavily used technology for transmitting and receiving data, such as National Crime Information Center (NCIC) data, from a patrol car to NCIC. Packet radio is a computer-to-computer communications mode in which information is broken into short bursts containing a message. The bursts (packets) also contain addressing and error detection information.³

One method for packaging data is called Cellular Digital Packet Data (CDPD). Additional discussion of this particular method is given in chapter 7.

A typical packet frame protocol as composed on a computer is shown in figure 6-23. The packet begins

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with a flag that signals the beginning of a frame. Next is the address of the packet, then the message or information data field, next an error-checking portion, and finally an end-of-frame flag. Usually about 1,000 bytes are transmitted in a packet. When the packet arrives at the address receiving computer, the packet information is stripped off and checked for errors.

If a message is so large that several packets must be sent, the field contains information for the computer to reassemble the original message in the proper order. If a packet is lost, the receiving computer acknowledges the loss to the originating computer, and the packet is resent.

There are several world standards for packet communications. One well-used standard for data packet transmission is CCITT X.25. Specialized software is required to run packet radio systems.
Current Public Safety Radio Systems

Paging Systems

Paging systems are single-frequency, one-way radio systems used for making people aware that they are being sought. The original local government pagers were voice pagers used for calling out volunteer fire departments (many of which are still in use). Modern pagers have alphanumeric readouts and are capable of storing a number of messages. Pagers are used by volunteer fire departments, police officers, emergency medical personnel, service personnel and technicians, and even children whose parents wish to keep track of them.

Very reliable commercial paging services are available in most regions of the United States at reasonable subscription rates. Many are used by local police, fire, and emergency medical services (EMS) units.

Alerts are given by a tone or a set of tones or by a built-in vibrator for use where tones are not permissible. There are many local and national suppliers of paging services and pagers.

Paging is accomplished at many different frequency bands including VHF, UHF, and FM broadcast. Two standards are especially popular at this time, but many others exist. These include the British Post Office standard, called POCSAG (Post Office Code Standardization Advisory Group), and Motorola’s FLEX™ system.

Statewide and nationwide paging is accomplished by transmitting the paging information over telephone lines or via satellites to paging transmitters for retransmission. When it is necessary to page over a wide area, a multitude of paging transmitters are activated at the same time in a simulcasting fashion.

The FCC has auctioned off a number of pairs of frequencies for two-way paging in the 900 MHz band (PCS narrowband). Each uses a 50 KHz bandwidth in one direction to accommodate high-speed data transmission, which is paired with either 50 KHz or 12.5 KHz in the reverse direction for returning data. The FCC also authorized some paging response frequencies for paging users who are already licensed under parts 22 and 90 of the FCC Rules, under certain circumstances.
Short Messaging Systems (SMS)

Short Messaging Systems (SMS) are capable of transmitting and receiving messages with up to 160 characters (like Western Union telegrams) with either a special modem using cellular technology or over a land line. The development has been confined to companies utilizing GSM networks in Europe and is just making its debut in the United States, where only a small number of systems are equipped to handle the GSM protocol. These include AT&T Wireless, Cingular Wireless and T-Mobile Wireless Corporation who offer some SMS capable phones. Other companies will follow as the technology becomes economical to use. As we write this, the number of U.S. users for SMS is few; however, it is estimated that as many as 20 billion SMS messages are sent monthly in the rest of the world.

The cell phone and/or PDA requires a keyboard and a wireless modem for the transmission of point to point data to an internet service provider (ISP). Specialized software allows a user to send and receive messages without being constantly connected to the internet service. Messages can be stored at the ISP station for forwarding once a cell phone is turned on and a connection is made. In other words, this is an e-mail service for a few characters which may be used for instant transmissions or for store and forward operation. Because of the limited number of characters, short cut methods similar to the 10-10 code (or amateur radio Q code) messaging system are used for repetitive messages.

In the civilian world, SMS is proposed for turning up the heat at home when leaving the office; turning on ovens to accommodate meals when arriving home; keeping inventories of food in freezers so a simple inquiry will deliver a grocery list to allow for a stop and purchase on the way home; and so forth.

The potential of running short messaging from a wireless radio or a land line may be an especially valuable tool for police surveillance to remotely turn on tape recorders, cameras or other apparatus. It may also be a methodology for the automatic transmission of smoke alarm information directly to a responsible fire department. Security still remains a problem to be solved in the near future until reliable, encrypted, and dependable SMS is possible. There will be many opportunities for SMS use in the overall justice system as usage increases.

Two-Way Simplex Radio Systems

Two-way radio systems using one frequency are called simplex radio systems. Base stations, mobiles, and handheld radios communicate on a single frequency. All new equipment being placed into service today for both VHF (excepting the 220 MHz band) and UHF bands is required to be 12.5 and 15 KHz wide, respectively, as required by part 90 of the FCC Rules. However, users with 25 and 30 KHz bandwidth equipment may continue to use their existing systems.

Base stations usually have high antenna installations to make sure that they can attain the desired radio coverage area. One problem with a simplex system is that handheld and mobile radios cannot communicate very far with each other because of their low antenna heights and are usually limited to just a few miles in flat terrain. Therefore, the person at the base station must repeat transmissions from one mobile to another. To alleviate this situation, the mobile relay or repeater was developed.
Two-Way Mobile Relay Systems

Two-way mobile relay systems are also called mobile repeaters, or just plain repeaters. In this discussion, these terms are used interchangeably.

The repeater makes use of two frequencies. The repeater radio functions as an amplified relay station receiving high- or low-power base stations, low-level mobile, and handheld radio signals, changing their frequency, amplifying the signals, and re-transmitting them on the repeater output frequency. Figure 7-1 shows the use of frequencies in a repeater configuration. In the figure, $f_1$ is the output frequency of the repeater and the input frequency to all base, mobile, and handheld radios and $f_2$ is the output frequency of the base, mobile, and handheld radios and the input frequency of the repeater. Repeaters are generally installed on the highest points within the coverage areas, including high buildings and mountaintops where the topography allows for maximum coverage and penetration. Thus, regardless of the output or the antenna heights on handheld, mobile, and base radios, the repeater signal is always the same strength at any receiving site.

Twice the bandwidth of a simplex system is now required, further aggravating the spectrum efficiency problem. Voice FM simplex and repeater radio systems suffer from other disadvantages too. For example, when a base or repeater station is placed on a high point, it can cover distances of 60 miles or more in radius and thus, although not usually needed by the licensee, negates the option of relicensing the frequency to another user up to 120 miles from the licensee.
Repeater Innovations

Repeater stations are usually high-power stations, 600 to 3,500 watts ERP, and cover a large area. Handheld radios, with their low output power of 0.5 to 3 watts ERP, are often unable to be heard at the repeater site, particularly in hilly or mountainous terrain or in urban areas having numerous tall buildings. To correct this power imbalance, one or more satellite receiving sites may be set up in these coverage areas close to the low-power radios to receive the low-power signals. Each satellite receiver’s output is sent via telephone line or microwave radio transmission to a signal comparator at a central site, where the strongest signal is selected through “voting” and utilized to drive the repeater. The scheme is shown in figure 7-2.

Another scheme used where there are problems transmitting to and receiving from mobiles and handheld radios due to large changes in topography requires several repeaters at different locations that may be switched at a central position, usually at the police communications dispatch center, to the repeater receiving the highest signal level. In this way the signal is “steered” toward the station, as shown in figure 7-3.

Where very large areas are to be covered, for example several counties, simulcast systems using multiple repeaters operating on the same frequency may be employed. In this case, all transmitters operate simultaneously and send a composite signal to receivers in the field. Special emphasis must be placed on frequency stability of the carriers, for they must be within a few Hertz at all stations; the modulation must be transmitted at exactly the same time, or there will be interference in the overlap zones of the repeaters.
Frequency and time stability can be accomplished by the use of microwave communications systems or by using the clock signals received from a global satellite system (such as GPS).

**Mobile Repeaters**

Small vehicular repeaters have been used to relay transmissions from handheld radios through the main vehicle radio to headquarters when an officer is in an area where he or she cannot reach the base repeater. An example of this is when an investigator, located in the concrete basement of a shopping center, can use a small 450 MHz repeater in the investigator’s vehicle to bridge communications between the basement and headquarters.

These repeaters have been used traditionally in the 150 and 450 MHz bands, and the concept is being explored for 800 MHz use by agencies and frequency coordinators.

**Trunked Radio Systems**

Public safety organizations have traditionally used dedicated repeaters. For example, in many communities, separate repeaters are used by the police department, the fire department, administrative departments, and road maintenance department, although the transmission loading is unequal for the departments most of the time.
If a police department needs to use two repeaters for operation and the road maintenance department’s repeater is available, the police department may be unable to use it. To use it requires that the police department’s mobiles tune their receivers to road maintenance’s frequency and that the police dispatch has an extra base station to contact the road maintenance repeater. This scenario is not very practical.

A repeater cannot be borrowed by another user, so it often sits vacant on a usable frequency while a user needing to transmit more information on his or her radio system must wait until their own repeater is free. To solve this problem and to improve the spectrum efficiency, the industry developed a “trunked” system concept borrowed from the telephone company industry.

With reference to figure 7-4, one can think of this as a box containing a number of repeaters, each of which may be switched into a radio circuit as needed. For example, if there are five trunked repeaters and repeaters #1 and #2 are in use, a central controller will designate #3 as the next repeater to be used when the need arises. If #1, #3, #4, and #5 are in use, it will designate #2 for the next user. In this way, repeaters do not stand vacant and the spectrum is more fully used.

When it issued rules for the 800 MHz band, the FCC required that most licensees requiring five or more channels must use a trunked radio scheme. Systems in place before the regulation was issued are “grandfathered in” and may continue to add single repeater stations as necessary.

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4 FCC Docket 18262.
Two technological breakthroughs have made trunked radio systems possible: 1) the development of microprocessors and personal computers, with their associated software and 2) synthesized frequency generators. Microprocessors allow the logical selection of frequencies for the repeaters. Frequency synthesizers at the repeater and mobile and portable stations allow the radios to set up individual transmitting and receiving frequencies as designated by the base station microprocessor called the “central controller.”

One scheme used to inform the central controller that there is a need for a repeater is a dedicated data control channel (repeater), which monitors mobiles and handheld stations at the base station. If a user desires to speak with another user or a group of users, he or she initiates a transmission on the data control channel indicating his or her ID number and requesting that he or she talk with another user or a group of users by indicating the group’s or individual’s ID number. The control channel repeater acknowledges the transmission, and the central controller determines the available repeater and commands the initiator and the target station(s) to change their operating frequencies to that of the assigned repeater. Typically within 1/4 second, a voice conversation may then take place. After the conversation, the radios return to monitoring the control channel and the central controller determines that the repeater is now available for other use. Note that these systems are totally software driven.

Besides dedicating a single repeater for control, there are other schemes that can be used. For example, the control channel may be rotated from one channel to another. Each time it is moved, the subscriber’s units must change frequency and track it.

Trunked radio systems are generally used in the 700/800/900 MHz bands. The latest FCC Rules now allow for trunking on public safety spectrum below 512 MHz, provided that these systems do not interfere with existing radio systems in surrounding areas.

Major U.S. suppliers of trunked radio systems are Motorola, the EFJohnson Division of EFJ, Inc., and the M/A-COM Division of Tyco International.

**Specialized Mobile Radio (SMR)**

Besides local government and law enforcement, trunked radio systems are used by large electric, gas, oil, and other industries to improve their efficiencies. A specific class of service, called “specialized mobile radio” was designated by the FCC to allow the set up of trunked systems that could be used to sell radio services to commercial and government users. The authors discuss these offerings later in this book as a reliable option, where available, for law enforcement.

The channel bandwidth set up for trunked activities is 30 KHz wide in the 800/900 MHz band. Original applicants used analog radios; however, enhanced specialized mobile radio has been the name given for digital SMR systems. Nextel is one supplier providing ESMR services nationally. Commercial services of trunked SMRs and ESMRs also are examined later in this guidebook.
**APCO Project 16 Trunked Radio System**

The Law Enforcement Assistance Administration (LEAA) in 1977 provided a grant to the Association of Public-Safety Communications Officials International (APCO) to make possible the opportunity for the public safety community to develop test beds and study various parameters associated with UHF band trunking systems.

APCO Project 16 members were charged with evaluating the technical, economic, and regulatory questions raised by the 800/900 MHz spectrum made available by the FCC. Studies were made on three experimental systems in Chicago, Miami, and Orange County, California.

When the study was completed, APCO published a document defining the mandatory and desirable functional capabilities for a public safety analog trunked radio system. It was issued in March 1979 and was called *900 MHz Trunked Communications System Functional Requirements Development*. The requirements were tailored for law enforcement and addressed channel access times, automated priority recognition, data systems interface, individuality of system users, command/control flexibility, systems growth capability, frequency utilization, and reliability.\(^5\)

APCO 16 trunking systems are presently being used by many large and medium-sized government agencies. To make the technology available to smaller government groups in adjoining cities, some communities are sharing systems. This has cut down on both capital investment and operating costs for any single entity.

The APCO 16 specification had no interoperability or encryption requirements; thus systems supplied by different manufacturers do not talk to one another. This limits competitive bidding for expansion and replacement parts.

A new digital system specification, under the Project 25 Steering Committee, has been in process for years to correct some of the interoperability difficulties, improve spectrum efficiency, and take into account the changing world to more efficiently and economically manufacture digital radio systems.

**Project 25 Digital Trunked Radio System**

In 1989, APCO, the National Association of State Telecommunications Directors, and a group of federal agencies jointly formed a working group called Project 25 (or P-25) to undertake development of a series of standards to define a digital radio system (conventional and trunked). Current federal sponsors include the Federal Law Enforcement Wireless Users Group (FLEWUG), National Communications System (NCS), and the National Telecommunications and Information Administration (NTIA). Other agencies and organizations (including the Department of Defense, APCO Canada, and the British Home Office) have all contributed to this effort in ensuing years, resulting in a worldwide standard for digital public safety land mobile radio. The Telecommunications Industry Association has provided ongoing technical and standards development.

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development support. The resulting suite of standards has been approved by the American National Standards Industry (ANSI) as a national standard (the ANSI/TIA/EIA-102 series). Completed standards include conventional and trunked radio for phase I (12.5 kHz bandwidth) and Phase II (6.25 kHz bandwidth) FDMA architectures. Work is in progress on TDMA standards for 12.5 kHz (2-slot) and 25 kHz (4-slot) TDMA architectures.

The objectives of Project 25 are: to maximize spectrum efficiency; to ensure competition in life cycle procurements; to allow effective and efficient inter- and intra-agency communications; and to provide “user-friendly” equipment and operation. Services defined include digital voice address including individual, group, and broadcast calls; circuit data including protected and unprotected data; packet data; and a set of nine supplementary services including encryption. Both conventional and trunked air interface specifications are included. The specification will be used for unit-to-unit direct communications, base station to limited field units, multisite simulcast, voting receiver systems, and wide and local area trunking at frequencies from 100 to 1000 MHz.

As stated above, the APCO Project 16 standard resulted in a number of competing analog systems that were unable to communicate with one another, and high on Project 25’s list of requirements is a common air interface between systems of different manufacturers enabling interoperability. In addition, there are common interfaces spelled out for the data port for laptop and other terminals, the host computer and other networks, the public telephone system interconnect, the network manager, and for connecting multiple systems (inter-system). Thus, competing companies may design their own offerings provided the common interface requirements are met.

After a number of different systems were investigated, the committee chose an FDMA access scheme proposed by Motorola, Inc. The scheme initially involved 12.5 KHz channel bandwidth, later to migrate to 6.25 KHz bandwidth.

A migration strategy has been defined in Project 25 that allows forward migration to 6.25 KHz bandwidth and backward migration to 25 KHz trunked radio systems, including the APCO Project 16 systems. The system is heavily software driven, and Motorola has licensed its scheme and software to other vendors without royalties so that other vendors may produce Project 25 compliant systems in competition with them.

The 12.5 KHz air interface has been published, although the data port, data host, and network management interfaces are still being worked on.

Several large-scale Project 25 systems are now in use, including State government systems for Florida, Michigan, and New Hampshire.
The Federal government (including Department of Defense for base operations) has mandated Project 25 for its digital systems throughout the U.S. Likewise, the American Association of Railroads has standardized on Project 25 for all railroads in North America.

**TErrestrial Trunked RAdio (TETRA)**

While the Project 25 committee elected to standardize on a FDMA scheme for the 12.5 KHz first phase of Project 25, a European standards committee selected a TDMA trunking technology it called TErrestrial Trunked RAdio (TETRA). TETRA uses 25 KHz of bandwidth that allow packet-switched data at rates up to 28 kbps. The standard can provide up to four voice or data channels within a 25 KHz bandwidth, thus providing the equivalent efficiency of a single channel of 6.25 KHz (which is required in Phase 2 of Project 25). The Project 25 steering committee is considering the integration of TETRA technology within Phase 2. Over-the-air interoperability and other standard interface requirements of Phase 2 still need to be met. The first TETRA law enforcement communications system was employed in Finland using Nokia equipment. Motorola has supplied a system to public safety organizations for the Island of Jersey (United Kingdom), New Zealand, Poland, and Hong Kong. These systems use trunked radio configurations driven by software, so that many different schemes may be dynamically employed to adjust to different situations.

**220 MHz Narrow Bandwidth Band**

The FCC reallocated the frequencies from 220 to 222 MHz for narrow bandwidth communications use. The channel bandwidth in this frequency band is only 5 KHz so as many as six channels may be substituted for a single 30 KHz FM channel (i.e., six signals where there was one, with a subsequent increase in spectrum efficiency of 5:1). See figure 7-5. The FCC has auctioned off frequencies in this band for regional and nationwide licensing.

One method to accomplish getting a voice channel within 5 KHz is to use a type of modulation called “amplitude companded single sideband” (ACSB). Other narrowband techniques were developed along with ACSB, some resulting in the ability to transmit voice and data at rates up to 16.8 Kbps.6

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Cellular Radio/Telephone Systems

Cellular mobile radio was developed by AT&T. Originally, two licenses were awarded in each coverage area: one to a wire company and the other to a wireless company in almost all metropolitan and rural areas. The cellular scheme allows for a large number of users over a given coverage area to connect to the Public Switched Telephone Network (PSTN). A great deal of the United States is now covered by cellular radio, and many law enforcement departments use cellular to supplement their radio communications systems.

The cellular system employs a number of coverage cells within a geographical area, as shown in figure 7-6. Each cell uses a trunked radio system to supply repeaters to users within the cell. Cells are connected to a Mobile Telephone Switching Office (MTSO) by trunked phone lines, fiberoptic cables, or microwave links. Cells can range from 30 miles down to 0.5 miles in diameter. When a cell reaches the maximum capacity of subscribers, it may be divided in two by adding new antennas and trunked radios and reducing power output to double the original capacity.
When a cellular telephone is turned on, it automatically registers with the local cellular carrier, and an indicator shows whether there is sufficient signal to connect to a cell. When a number is called, a dedicated radio control channel receives the information and sends it through the MTSO to the PSTN system to ring the called person’s number. When the call is answered, the MTSO sets up a dedicated cell repeater for the subscriber to use for the conversation.

During the time of the conversation, the cell phone signal strength is monitored at the cell where the conversation is taking place, as well as at adjacent cells. If the signal strength gets stronger in another cell, the MTSO requests that a new repeater in that cell take over the conversation. The “hand-off” is accomplished seamlessly within 1/5 of a second. When the conversation is completed and the subscriber hangs up, the MTSO returns the repeater channel for use in another phone call.

If a call is made from the PSTN to a cellular subscriber, a set of dedicated paging channels at all the cell sites calls the subscriber’s number. When the subscriber’s cell phone hears the page, the called subscriber answers the cell phone and the phone signals back through the control channel that the call has been answered. This triggers the MTSO to set up a repeater for the conversation. When the subscriber hangs up, the MTSO releases the channel for another call, as described above.

The original cellular system, called Advanced Mobile Phone System (AMPS), uses frequency modulated repeaters with 30 KHz of bandwidth in each direction for one conversation. To improve the spectrum efficiency, a frequency division multiplexing system allowing three 10 KHz channels in the 30 KHz bandwidth was developed called Narrowband Advanced Mobile Phone System (NAMPS). As the service developed over the years, several even more efficient technologies were developed using time division multiple access (TDMA) and code division multiple access (CDMA), which are discussed in the previous chapter.

Characteristics of cellular systems include:

1. A very large number of subscribers can be accommodated.

2. As the subscriber numbers in a cell reach the cell capacity, the cell may be divided to double its capacity.

3. By keeping the transmitter power low in each cell, transmitting frequencies may be repeated in nearby cells, thus increasing spectrum efficiency.
4. Cellular radio systems tend to be very reliable even under the worst environmental conditions.

5. With the various modulation schemes now being used, every cell phone does not work in every system. However, multimode phones have been developed to solve this problem.

**Personal Communications Systems (PCS)**

Because of the need for more frequencies for personal communications and the popularity and demand for cellular radio, the FCC reallocated several megahertz of frequencies in the 900 MHz range and a large portion of the 2 GHz band for PCS. These frequencies were auctioned off to the highest bidder by the FCC.

The 900 MHz spectrum is allocated into 50 KHz channels, some paired with other 50 KHz channels and some with 12.5 KHz channels. These are being used for two-way paging, data transmission systems for carrying stock market and other information, and other uses conceived by the auction winners.

The 2 GHz band was auctioned off in much larger bandwidth segments, up to 30 MHz. (A small portion of the band was allocated for unlicensed operation to operate wireless PBX’s and other in-building voice and data communications networks.) The broadband spectrum contains very few technical limitations for service offerings so that companies with unique communications schemes might make creative use of the spectrum. However, so far, most offerings made public appear to be for additional cellular radio systems.

Buildouts are proceeding initially in high-density population areas where licensees can get a quick payback, so many rural areas may have to wait for service. Because of the number of winners in various areas, there may be as many as six competitors in the densely populated areas.

Some seven different de facto technical approaches to these new cellular radio systems exist, so a telephone used in one system will not necessarily work with another. Some confusion also exists between the 800 MHz cellular services and the 2 GHz PCS cellular services because of advertising claims. Today, technologies used for cellular and PCS are basically the same and the offerings are very similar. However, PCS has the potential to provide other services in addition to cellular. People must wait and see as the technologies mature.

**Cellular Digital Packet Data (CDPD)**

Cellular Digital Packet Data, or as it’s more commonly called, CDPD, consists of using cellular radio repeaters for the transmission of small bursts of data known as packets. The CDPD process allows the insertion of packets of data in between lightly modulated cellular radio voice channels without reducing cell phone voice capabilities. CDPD is an open transmission methodology for sending data on existing Advanced Mobile Phone Service (AMPS) cellular networks at a transmission rate of 19.2 kilobits per second. The need for sending digital packet data has increased over the years, so dedicated CDPD channels

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7 FCC Rules and Regulations, Section 24.129, Frequencies.
have been set up by some of the cellular providers. With the recent FCC decision to allow cellular carriers to drop AMPS analog service in 2005, CDPD may no longer be available after that time.

Law enforcement agencies have found that using laptop computers to obtain critical information in patrol cars without having to go through radio dispatchers improves their officers’ efficiency, decreases the information delivery time, and reduces errors. Using CDPD to bypass a dispatcher, field officers may obtain information directly from local, state, or NCIC databases to check driver’s license validity, existing warrants, and other information that may be of use to an officer in processing a suspect.

The option of using CDPD minimizes the capital outlay by a public safety agency, since it is only necessary to purchase the in-vehicle equipment (e.g., laptop computers with modems and software) rather than purchasing the entire radio communications network for data transmission support.

CDPD pricing is sometimes based on the number of bits transmitted, which is difficult to estimate for budgeting. Recognizing the fixed budget nature of public safety departments, many vendors now offer fixed monthly fee contracts.

The network architecture uses the protocol used in the Internet (i.e., Transmission Control Protocol/Internet Protocol, or TCP/IP). Therefore, any standard personal computer modem that works with the Internet will operate with a CDPD system; however, special software must be used.

Public safety agencies wanting to use CDPD should check with cellular service providers in their region to see if they offer CDPD. Then they need to carefully check coverage to make sure that their operating area is adequately covered. Most cellular radio suppliers provide coverage diagrams for subscribers, and many are available instantly over the Internet. A major drawback to some CDPD systems is that the data system competes with the voice component of the system, and can often face severe delays during peak usage (such as commute times) when public safety may have its highest demand for service.

Point-To-Point Microwave Communications Systems

Often you need to connect telephone circuits from one terminal to another, voice and control circuits to repeaters and trunked systems, voting receiver inputs from satellite sites to a comparator, T1 (1.5 Mbps) or T3 (45 Mbps) data circuits, and other communications circuits from one point to another point. Generally, these needs may be fulfilled economically and reliably by leasing wire or fiber-optic circuits from the local telephone or cable company.

When a telephone company expands capacity, it usually overbuilds to allow for future customers. If the circuits exist, leasing payments involve only operational and maintenance costs. However, if the circuits do not exist, you must pay the up-front capital costs involved in constructing the new facilities.

The economies of building a private microwave system usually are in your favor when it is necessary to provide service to an area that would require new facility construction by the telephone company.
The microwave bands include frequencies generally above 960 MHz, or approximately 1 GHz. (Frequency bands used for commercial purposes are in the 960 MHz and 2, 4, 6, 11, 18, and 23 GHz areas.) The 960 MHz band can be used to transmit up to 15 narrowband voice or data channels; the other frequency bands have considerably wider bandwidths to accommodate many more voice and data channels. Microwave systems may be either analog or digital radio systems.

Microwave propagation is considered “line of sight” (LOS), so transmissions must be repeated at approximately 25-mile increments in bands up to 12 GHz. In mountain areas, the spacing may be as great as 60 miles. Above 10 GHz, rain attenuation usually causes a distance limitation, so repeaters must be more closely spaced depending upon the amount of rain in different parts of the country.

**Microwave System Engineering and Licensing**

A typical microwave system requires several engineering criteria to be met. The first is that the path between two microwave terminals must be free of obstacles which might impair the wave front as it travels between terminals. The second requirement is the signal strength must be high enough to meet either the signal to noise ratio requirements (for an analog radio system) or the bit error rate requirements (for a digital radio system) for a maximum allowable path outage time. The last condition is the path must be free from either causing interference to another microwave communications user or receiving interference from another user. A typical path profile to meet the first condition is shown as figure 7-7.

Most microwave communications systems require FCC licensing under Part 101 of the FCC Rules and Regulations. Frequency coordination is required and the applicant must utilize the FCC’s Universal Licensing System (ULS) at the FCC website (see resources in appendix B) for all applications. There is a class of microwave systems not requiring licensing by the Commission under Part 15 of the rules.

Most unlicensed systems use spread spectrum modulation which spreads the power over a large bandwidth. The unlicensed systems must still meet the above engineering requirements excepting there is no interference protection available.

Additional information regarding licensing is given in chapter 8.
Wireless Local Area Networks (WLAN)

Wireless LAN technologies are rapidly becoming integrated into public safety wireless infrastructures in North America and Europe. Carrying data at speeds up to 54 megabits/second, these inexpensive off-the-shelf technologies offer interesting capabilities when properly incorporated into the wireless environment. Because these technologies operate at frequencies above 2 GHz, they typically provide very short range communications (100 to 500 feet). Thus, coverage is characterized by operational "hot spots" with a radius of several hundred feet rather than seamless coverage across a wide area. The central "base station" serving a hot spot is called a wireless access point or WAP, an off-the-shelf device costing $100-200. WAPs typically connect to a wired network via a standard connection such as 10- or 100-baseT. Field terminals are typically linked to the WAP with a simple wireless card that plugs into a PCMCIA slot.

The technology, often called 802.11 after the designation assigned to this class of standards by the Institute of Electrical & Electronic Engineers (IEEE) who developed the standards, is an alphabet soup of protocols (a, b, e, f, g, h, i and 1x), as indicated in table 7-1.
Table 7-1. IEEE 802.11 Protocols and Standards

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Band</th>
<th>Data Rate or Description</th>
<th>Physical Network</th>
<th>Standard Completed?</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>5 Ghz</td>
<td>6 to 54 Mbps</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>b</td>
<td>2.4 Ghz</td>
<td>1 to 11 Mbps</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>e¹</td>
<td>All</td>
<td>Quality of service standard</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>f²</td>
<td>All</td>
<td>Inter-access point interoperability</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>g</td>
<td>2.4 Ghz</td>
<td>Up to 24 Mbps</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>h³</td>
<td>All</td>
<td>Dynamic frequency and power control</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>i⁴</td>
<td>All</td>
<td>Enhanced hotspot security standard</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>lx</td>
<td>All</td>
<td>Network authentication protocol standard</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

¹ Without strong quality of service (QoS) assurance, the existing version of the 802.11 standard doesn't optimize the transmission of voice and video. 802.11e will improve QoS for better support of audio and video applications. It will apply to all 802.11 wireless LANs and should be implemented as a simple software upgrade to existing products.

² The existing 802.11 standard doesn't specify the communications between access points in order to support users roaming from one access point to another. The problem, however, is that access points from different vendors may not interoperate when supporting roaming. 802.11f is currently working on specifying an inter-access point protocol that provides the necessary information that access points need to exchange to support the 802.11 distribution system functions (e.g., roaming). In the absence of 802.11f, you should utilize the same vendor for access points to ensure interoperability for roaming users. In some cases, a mix of access point vendors will still work, especially if the access points are Wi-Fi-certified. The inclusion of 802.11f in access point design will eventually open up your options and add some interoperability assurance when selecting access point vendors.

³ 802.11h is being developed for the European market.

⁴ 802.11i is actively defining enhancements to counter the issues related to wired equivalent privacy (WEP), making your wireless network as secure as your wired network. The existing 802.11 standard specifies the use of relatively weak encryption keys without any form of key distribution management. This makes it possible for hackers to access and decipher WEP-encrypted data on your WLAN. 802.11i will incorporate 802.1x and stronger encryption techniques, such as the Advanced Encryption Standard (AES). It should be possible to upgrade existing access points with software upgrades. The implementation of AES, however, may require new hardware.

802.11b Networks

The most common network now being implemented is 802.11b. These networks are being installed by both the public and private sectors, including many private businesses and residences. Using a series of WAPs around an agency's service area tied back to its wired backbone, it is possible to rapidly transmit large amounts of non-time critical information (such as reports) back to a central point, or to distribute information (such as bulletins and photos) out to field units. By placing WAPs at locations where mobile terminals often congregate, such as headquarters, precinct houses, fire stations, hospitals, public buildings or near major travel routes, specialized software applications that detect connectivity to the WLAN will automatically transfer waiting data when in range of the system.
Figure 7-8. Phoenix, Arizona, Fire Department Mobile Computer Terminal System Using WLAN
The left side of figure 7-8 depicts the system used by the Phoenix, Arizona, Fire Department to link its mobile fire apparatus to its wired data network using 802.11b. WAPs are located at fire stations, the training academy and the service shop. Information that is automatically and routinely updated includes maps, hazard and inspection information, aerial photographs, and general information files. The system is also capable of automatically updating software applications on the mobile terminals.

In standalone applications, a mobile-mounted WAP can be used to link video cameras, terminals and other data-intensive applications from a command post vehicle at the scene of a major incident to each other and (via other wired or wireless links) back to a central system. Command post vehicles such as the InfraLynx provided by the US Department of Justice with its Prepositioned Equipment Pods for response to weapons of mass destruction incidents provide the capability to link real-time data and video applications to local and/or remote applications (see figure 7-9).

Figure 7-9. InfraLynx Mobile Command Post

**Wireless Local Links - Bluetooth**

Electronic devices interconnect to each other in a variety of ways. Computers have a CPU, keyboard, monitor and mouse that all connect with different cables. Your TV set, VCR, and cable box all interconnect with cables, while each generally has its own wireless remote control unit. Your personal MP3 player connects to a pair of headphones with a wire lanyard. Each of the various pieces and parts of these systems makes up a community of electronic devices that communicate with each other using an assortment of cables, infrared beams and radio waves, and a more complex set of connectors and protocols.

Suppose there was a way for all of these devices to intercommunicate with each other without wires and without the necessity for human intervention. This is the concept known as Bluetooth. More than 1000 electronic equipment manufacturers worldwide have jointly developed a specification for a very small radio
module that fits into many kinds of electronic components. These include cell phones, computers, headphones, keyboards, PDAs and a multitude of similar devices.

Bluetooth operates at two levels. At the basic physical level, it is a radio frequency standard operating at 2.45 GHz. It is also a link-level standard that defines how and when data bits are sent, what each means, and how all involved devices assure that what is being sent by one device is the desired message received by the other device(s). It is a technology that is designed to operate without human intervention once a device is turned on in the presence of other devices with which it is designed to communicate. By its very nature, it is designed to be very short range. The transmitter power limit of 1 milliwatt limits the range of Bluetooth technologies to about 30 feet between devices.

When Bluetooth-enabled devices come within range of each other, a wireless communication automatically takes place during which it is determined if the devices have data to share, and/or if one needs to control the other. Each device has an address assigned from a group of addresses reserved for each class of devices. When one Bluetooth device detects another, this address range is searched to see if the new device is a companion device.

If there is a need to communicate, the devices form a personal area network (PAN, or piconet) that could fill a room (for a computer or stereo system), or simply link an MP3 player on the belt to a set of headphones being worn by the user. Different piconets establish their own random frequency hopping algorithm, limiting interference between devices within range of each other. Communications speeds vary from 57 kbps in one direction and 721 kbps in the other, to a bi-directional speed of 432.6 kbps.

With such a wide range of Bluetooth devices, interference is an important consideration. Bluetooth uses spread-spectrum frequency hopping across 79 random frequencies within a specified range at a rate of 1600 frequency changes per second. Thus, it is rare that two incompatible devices within range of each other would occupy the same frequency at the same time. Since the 2.45 GHz band is shared with non-Bluetooth devices, frequency hopping tends to limit the interference from these other devices. However, Bluetooth shares this radio band with a number of other industrial, scientific and manufacturing devices (including 802.11b and microwave ovens), a number of which may cause interference to Bluetooth devices. It is thus critical that public safety users carefully evaluate the environment where Bluetooth might be used. Bluetooth is especially not recommended for mission critical applications in a mobile environment because of the difficulty in isolating this technology from potential sources of interference.

Bluetooth technology offers the ability to move many public safety devices using several distinct components from the wired to the wireless environment. From headphones and keyboards to cameras and PDAs, Bluetooth technology is slowly entering the public safety marketplace, providing added freedom of movement to agency personnel.

Did you know?

Bluetooth is named after Harald Bluetooth II, King of Denmark. Harald - nicknamed Bluetooth - is famous for uniting Denmark and parts of Norway into a single kingdom at the end of the last millennium and for bringing Christianity to Denmark. His name was chosen for the standard to show the importance of the Scandinavian countries (Denmark, Finland, Norway and Sweden) in the International telecommunications industry, and to signify the intent of the Bluetooth Consortium to unify wireless connectivity.