

# Wireless Digital Communication

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## An Introduction to the Forward Link

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### ABSTRACT

This paper provides an introduction to wireless digital communication. The challenges facing wireless communication are Herculean due to the hostile air interface. A description of how the codec, vocoder, encoder, interleaver, and modulator elements may be optimized for the wireless medium is provided. Multiple access techniques such as FDMA, TDMA, and CDMA are also discussed. The advantages of spread spectrum over other methods are given particular attention. Several types of spread spectrum techniques such as Direct Sequence, Frequency and Time Hopping are discussed along with the theory behind these methods. Special attention is given to pseudo noise (PN) codes and how they are generated as well as how these codes are used to spread the desired data signal. The discussion is limited to modulation (forward link) of the communication channel rather than demodulation (reverse link).

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## INTRODUCTION

Communication systems are changing at an unprecedented rate. The explosion in wireless cellular communication is a case in point. There also appears to be no stopping as satellite based systems are already on the drawing board. In fact, some will be deployed and operational before the end of the decade. No longer will a user be tied to sparsely spaced highway cell sites.

The wireless medium is a scarce and precious resource. It is imperative that we manage it wisely and use technology that will aid in its efficient use. While UHF (300 to 3,000 MHz) and SVHF (3 GHz to 30 GHz) amplifiers, have advanced sufficiently to allow us to expand the upper end of the useful spectrum, the RF spectrum is not unlimited. RF engineers have pushed the upper end of the useful spectrum to 10 - 12 GHz and beyond. However, we are approaching the upper limit of the useful spectrum. Surprisingly, that limit is the medium itself. The atmosphere is effectively transparent at frequencies below 10 GHz. Between 10 GHz and 500 GHz, atmospheric attenuation varies from 0.01 to 50 dB/km. Below 100 GHz, the attenuation is less than 1 dB/km, an acceptable loss for most applications.<sup>1</sup> But above 100 GHz, losses in the medium make most applications impractical. For the foreseeable future, 100 GHz is the upper limit of the useful RF spectrum.

In light of this limitation, it is clear that careful and efficient use of the spectrum is necessary. The Federal Communications Commission (FCC) is charged with spectrum management and since the mid 90s the FCC has been selling the spectrum in auctions to pay for the national debt.

Clearly, we must make the best use of what we have. For the wireless telecommunication designer, that means using efficient modulation techniques. In this paper, we will introduce several techniques that represent the present state-of-the-art in digital communication. As we shall see, by using digital communication, we can process the signal using advanced techniques that would not be possible in the analog world.

## THE WIRELESS MEDIUM

The air interface places enormous restrictions on the design of a communication system. Terrestrial wireless communication is a harsh environment and extra-terrestrial even worse. Table 1 highlights the unique characteristics of the medium and the problems that need to be mitigated or solved to provide a robust communication link.

**Table 1 Challenges of a Wireless Medium**

- Unintentional interference such as lightning and RF noise pollution from microwave ovens are sources that the wireless medium must overcome.

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<sup>1</sup>Except in the O<sub>2</sub> absorption band (53 GHz to 67 GHz) where the attenuation is as high as 16 dB/km.

- Intentional interference (jamming) caused by users wishing to disrupt communication are very real world problems. The air interface is a vulnerable target. Wire-based communication systems can protect cables to reduce attack, not so with the wireless medium.
- Slow speed users (e.g., cars) means the communication channel environment is always undergoing change. Therefore once a communication link is established, it must be constantly monitored.<sup>2</sup>
- High speed satellites cause significant Doppler frequency shifts making the wireless channel particularly complex.<sup>3</sup>
- Short term fading is yet another obstacle. This fading occurs from multipath reflections of RF signals scattered by structures such as houses or buildings. This type of fading is referred to as short term since its duration is less than a second. This type of fading is often frequency dependent.
- Long-term fading, also called **shadowing**, is caused by changes in the terrain as the user moves. Long term fading is considered to last for several seconds or longer. Passing under a highway underpass or around a mountain range are typical examples. Long term fades are not typically considered to be frequency independent as they attenuate large portions of the spectrum.
- Very long term fading refers to periods of time measured in days and even years. For example, rain, poor air quality, and temperature inversions affect the communication channel for extended periods. In addition, frequency attenuation in the HF range (3 to 30 MHz) includes daily variations from the ionization of the ionosphere and longer term variations from the 11 year sunspot cycle.
- Frequency selective fading presents another hurdle. This fading is caused by constructive and/or destructive interference from multipath signals and typically changes very rapidly in a mobile environment.
- The air interface is very lossy. Wire based systems have very little signal loss, in fact, fiber optic based systems are virtually lossless. The wireless medium, on the other hand, exhibits large losses that rapidly increase with distance (e.g., inverse square). This is a particular challenge for satellite based systems where the distance between transmitter and receiver is measured in thousands of miles.

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<sup>2</sup> The maximum change in frequency is given by  $F = (2 * V_t * F_c) / c$  where  $V_t$  is the velocity of the source to the destination,  $F_c$  is the transmitting frequency, and  $c$  is the speed of light. For a car traveling at 60m/hr using a cellular phone at 900 Mhz, the Doppler shift is 180 Hz.

<sup>3</sup> Using the Doppler frequency shift relationship again, but this time for a fast moving satellite with a velocity of 25,000 m/hr, the Doppler shift at 900 MHz is 75 KHz, a very significant engineering problem which must be solved.

## THE SHANNON LIMIT

Before we discuss the components of the digital communication system, we need to look at the first law of telecommunications, the **Shannon Limit**. In 1948, the same year that the transistor was invented at Bell Labs, Claude Shannon, also at Bell Labs, made an equally monumental discovery. In what is now a classic in communication theory, "*A Mathematical Theory of Communication*" he proposed that channel capacity can be described as:

$$C = B \log_2 (1 + S/N)^4$$

where:

C = channel capacity, bits/sec  
 B = channel bandwidth, Hz  
 S = signal power, watts  
 N = noise power, watts

### Equation 1 Shannon Limit

and:

$N = N_0B$   
 $N_0$  = noise spectral density, watts/Hz  
 B = noise bandwidth

### Equation 2 Noise Relationship

The Shannon limit is the holy grail of telecommunications. Trying to exceed this limit is analogous to traveling faster than the speed of light or building a perpetual motion machine. The significance of the Shannon limit in real world terms is summarized in Table 2.

### Table 2 Implications of the Shannon Limit

- Channel capacity is a function of the bandwidth and the signal-to-noise ratio (S/N).
- If the data rate is less than the channel capacity, then error-free communication is possible on a noisy channel.
- You can send faster than the channel limit, but it will not be error free.
- To increase channel capacity one can either increase bandwidth, or increase the signal-to-noise ratio.

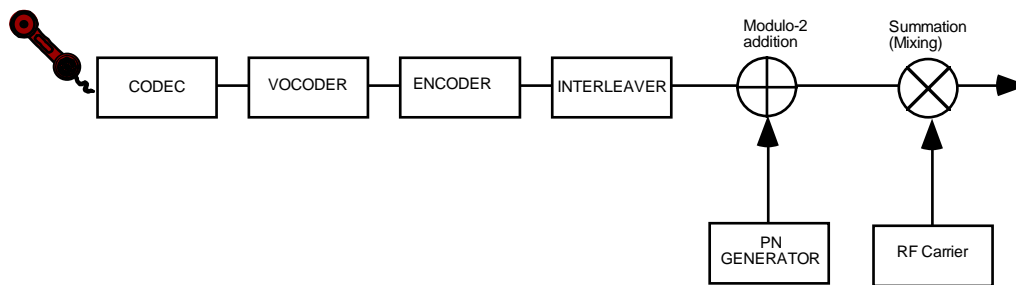
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<sup>4</sup> The formula applies only to Additive White Gaussian Noise (AWGN). The word additive is important here since it means that the relationship holds true only if the noise is added rather than multiplied by the signal. The word *white* means that the content of the power of the noise is constant over the frequency range. Theoretically, this is not possible since it would imply infinite power, however, in practice it is accurate. In addition, fading, interference, distortion, etc. are not considered.

It is this last characteristic of the relationship that is particularly important. To increase channel capacity we can either increase the bandwidth or increase the signal-to-noise ratio, but not with equal benefit. For example, if we double the bandwidth, we double the capacity. However, if we double the S/N ratio, we increase channel capacity by only 50%. Therefore, given a choice between changing bandwidth or S/N, and other things being equal, it is logical to opt for increasing bandwidth to increase channel capacity. As we discuss the transmission of data, we will return to this pivotal concept many times, particularly spread spectrum technology.

## TELECOMMUNICATIONS

The challenges facing a wireless medium are non-trivial and a **solution to reliable communication requires end-to-end optimization**. Each element of the system must be designed to insure effective and efficient communication. Optimizing a portion of a communication system will result in a less than ideal solution. With this in mind, let's examine the forward transmission of a signal as it passes through various stages. Figure 1 shows a generic digital spread spectrum communication system.



**Figure 1 Generic Spread Spectrum System**

### Codec

The first stage of the system is the **codec** (coder/decoder). Here, analog speech is digitized. For a standard telecommunication system, a codec is a logarithmic analog to digital converter (A/D) taking 8 bit samples. The 8 KHz sampling rate yields 64 Kbps **Pulsed Coded Modulation** (PCM). PCM is just one of several waveform coding schemes, however, it is widely used and easy to implement. In fact, it is an international standard (CCITT G711).

The sampling rate is based on the characteristic frequency spectrum of human speech and the Nyquist theorem. Nyquist showed that to accurately reproduce a signal, it must be sampled at twice the rate of the desired signal (8 KHz in our speech example). Note that the Nyquist rate is a theoretical minimum sampling rate. In the real world where electronic filters are less than perfect, less than optimal results are achieved. However, 3 KHz can be faithfully reproduced with an 8 KHz sample rate resulting in good speech quality.

Waveform coders in general can be broken into two broad categories: **time** and **frequency domain coders**. Pulse Coded Modulation falls into the time domain category along with **Differential Pulse Coded Modulation** (DPCM) and **Adaptive Differential Pulse Coded**

**Modulation** (ADPCM). Examples of frequency domain coders are **sub-band** and **transform** coders.

### Vocoder

A **vocoder** (voice coder) is responsible for compression. The output of a typical speech vocoder varies considerably depending on the compression algorithm. Typically, the 64 Kbps PCM output from the codec can be compressed from 14.4 Kbps to 1,200 bps. The quality of the speech is the prime consideration. The lower limit is achieved by taking advantage of the inactivity (silence) that comprises 40% of human speech on average. The higher rate provides the best speech fidelity.

Note that a vocoder is a special case of the more general **waveform coder** which makes no assumptions about the waveform. A vocoder, on the other hand, takes into account the unique characteristics of human speech. For example, in addition to the high level of speech inactivity, there is also a high correlation between adjacent speech samples. By using this characteristic, one can provide acceptable speech at very low data rates. Types of vocoders include: **channel**, **homomorphic**, **formant**, and **linear predictive** vocoders. Vocoding is a complex subject and much research is done in this area to provide intelligible speech with the least amount of data. Lower bit rates ultimately reduce RF bandwidth and power, the precious resource we are trying to conserve.

### Error Control Coding

Before discussing the next communication element, the **encoder**, we first must understand what the encoder does and why we use it. An encoder provides **error control coding** which adds information to a data stream to aid the receiver in detecting and/or correcting errors that may occur during transmission. This has the effect of making the communication system more interference resistant.

There is a normally a price that we pay for adding information, either power or bandwidth. However, the benefits of the additional information is compensated for by allowing the system to operate with the same quality of service in a worse (lower) S/N environment. Conversely, we can lower the transmitted power for a given S/N ratio. In essence, we are trading power for bandwidth. This advantage is referred to as the **coding gain** of the system. Let's quantify this concept by restating Shannon's channel capacity relationship in a slightly different form.

If we define:

- $E_b$  = energy per bit, joules (watt-seconds)
- $R$  = relative data rate, bits/sec/Hz (spectral efficiency)
- $N_0$  = noise spectral density, watts/Hz

Then using basic algebra, we can restate that for a system to comply with the Shannon limit, it must satisfy the inequality shown in Equation 3.

$$(E_b/N_0)^3 (2^R - 1) / R$$

### Equation 3 Channel Capacity Restated

The ratio  $E_b/N_0$  (pronounced *ebb-know*), describes the power efficiency of the system in dB. The relationship is plotted in Figure 2 and shows that a large R (many bits/sec/Hz) requires a large  $E_b/N_0$ . Conversely, a small R allows a small  $E_b/N_0$ .

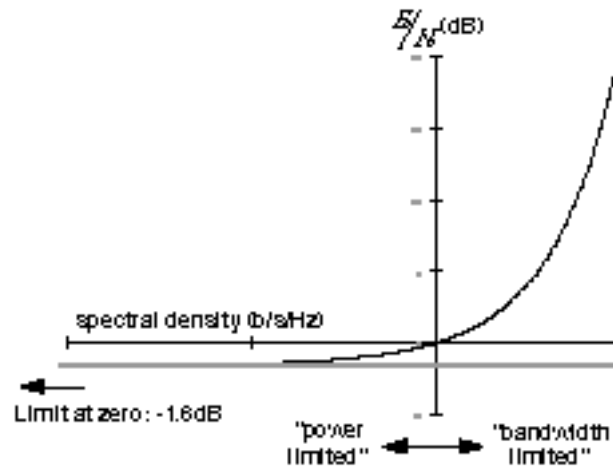


Figure 2 Minimum  $E_b/N_0$  vs. Bandwidth

## Encoding

The **encoder** provides **Forward Error Correction (FEC)**. This means the encoder adds error control coding to the data stream to help the receiver correct for errors. Two major types of encoders are **convolutional** and **block**.

Examples of block codes include **orthogonal** (e.g., Reed-Mueller), **Hamming** (e.g., CRC), **Golay**, **BCH**, and **Reed-Solomon**. These coding schemes are in widespread use. For example, Reed-Solomon is used in CD-ROMs during demodulation. In fact, the familiar **Cyclical Redundancy Check (CRC)** is a block code. More sophisticated methods not only check the integrity of the data, but also make corrections. For example, NASA uses encoding extensively to help insure the integrity of the data received from deep space missions such as the *Voyager*, *Galileo*, *Mariner 6*, and *Mariner 9* spacecrafts.

Convolutional codes are **sequentially** and **Viterbi** decoded and are relatively easy to implement. A typical encoder is shown in Figure 3. The length of the shift register,  $K$ , is referred to as the **constraint length** of the code. In our example,  $K=7$ . The number of taps chosen is referred to as the **code rate** expressed as a fraction. In the example,  $r=1/2$  since two summation points are tapped. The location of the tap points is yet another variable that is chosen according to the polynomial desired. For example, in the figure, the upper symbol tap points are 1, 3, 4, 6, and 7. The lower symbol is derived from tap points 1, 2, 3, 4, and 7. The symbols are computed using modulo-2 addition and then mixed into a single output.

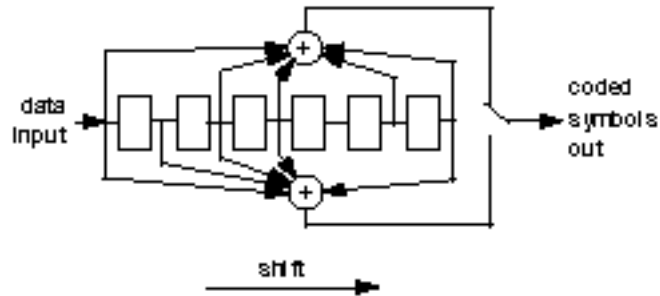


Figure 3 Convolutional Encoder<sup>5</sup>

When the original data **bit stream** is encoded, the output data stream is said to consist of **symbols** and not bits. This terminology is used to help differentiate it from the term **bit** which normally refers to the original data. The coding algorithm determines the relationship of a bit to a symbol which is typically 2 to 4 symbols per data bit. Specifically, a code rate of  $r=1/2$  means that 2 symbols are used to encode a bit. Similarly, in a  $r=1/4$  system, 4 symbols encode a single bit. The information added by the encoder is in the form of **parity symbols**.

### Interleaving

As its name implies, an **interleaver**, scrabbles or interleaves the symbol stream. There is no information added or removed. The interleaver merely moves the position of the existing symbols in a block. If we look at the interleaver in isolation, it is difficult to explain why this process is performed. However, interleaving is very useful. During fast fading or atmospheric lighting crashes we may lose a few milliseconds of data which corrupts small portions of the data stream. Without interleaving, this corrupted data might sound like a pop or click to a user due to the abrupt characteristics of the error. However, interleaving spreads the symbols evenly in a block, resulting in the corrupted symbols also being distributed. While symbols are lost in both cases, through interleaving, the user is often not aware of the errors.

Another reason for interleaving symbols comes during demodulation when the decoder extracts the stream. A decoder has a much better chance at correcting errors when the symbols are evenly spread through a block.

Figure 4 shows a common implementation for an interleaver. Code blocks are written into memory in **rows** and read out from the memory in **columns**. The effect is to spread the data. At the receiver, the process is reversed.

A problem facing the interleaver designer is the length of the block to interleave. A block must be relatively short since we have real-time constraints. For example, in commercial telephone applications, interleaved block lengths are 20 ms.

<sup>5</sup> Source: *Error Control Coding Seminar* by Phil Karn presented at the February 1995 Tucson Amateur Packet Radio annual meeting. Available in post script format at: <http://www.qualcomm.com/people/pkarn/ham.html>.

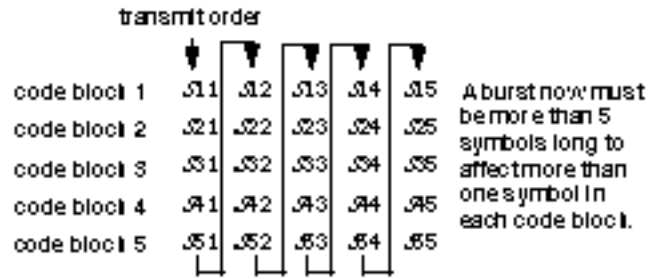


Figure 4 Interleaving Example<sup>6</sup>

### DIVIDING THE SPECTRUM

Our primary design goal is **capacity**, the ability to provide a specific level of performance for as many users as possible. To increase capacity, we need to allow multiple users to access the spectrum. Let's look at some of the more common multiple access methods. Multiple access methods techniques include: **Frequency Division Multiple Access (FDMA)**, **Time Division Multiple Access (TDMA)**, and **Code Division Multiple Access (CDMA)**. Figure 5 shows how the spectrum is utilized in each of these methods.

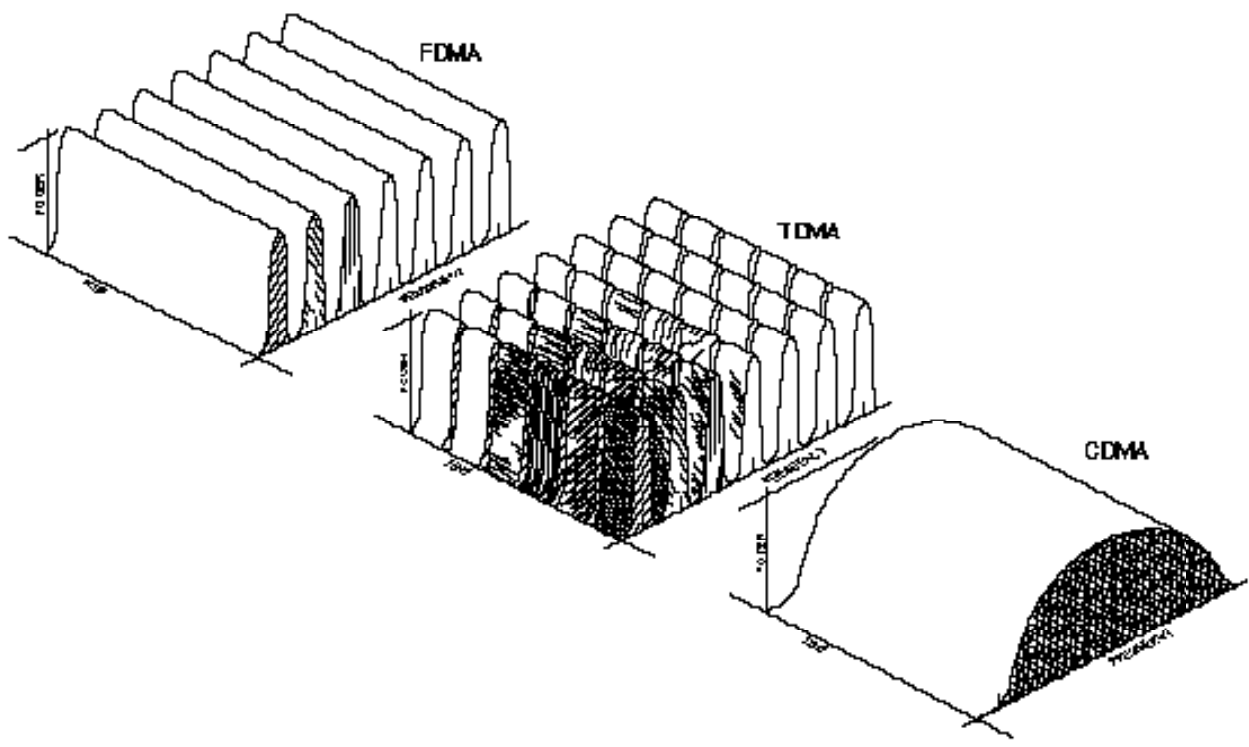


Figure 5 Multiple Access Methods

<sup>6</sup> Source: *Error Control Coding Seminar* by Phil Karn presented at the February 1995 Tucson Amateur Packet Radio annual meeting. Available in post script format at: <http://www.qualcomm.com/people/pkarn/ham.html>.

## FDMA

Frequency Division Multiple Access is the most basic and easiest understood multiple access method. Examples of FDMA systems are commercial AM, FM, and TV stations.

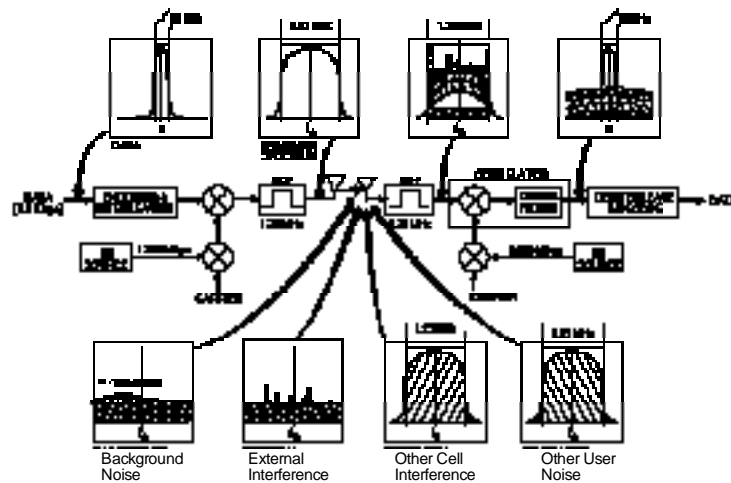
One could argue that FDMA is really not a multiple access method since each station is given its own dedicated frequency. However, they are sharing the spectrum and thus fall into the category of multiple access. In practice, many stations actually do share the same frequency under FDMA. For example, a TV station transmitting on channel 2 in one city, may share that same frequency with hundreds of other stations transmitting on channel 2 in other parts of the country. Interference between these stations is prevented by RF propagation characteristics. Specifically, terrestrial stations transmitting on frequencies above approximately 50 MHz<sup>7</sup> are limited to line-of-sight communication, typically 30 to 50 miles.<sup>8</sup> Therefore there is a natural separation of the stations provided by distance.

## TDMA

Time Domain Multiple Access, as its name implies, allows stations to share the frequency spectrum in time. Various international and national standards have evolved which specify in detail the number of stations that share the frequency slot and the duration that each may use it.

## CDMA

Code Division Multiple Access is a complex and unique form of multiple access communication using spread spectrum modulation. Figure 6 shows the components of a CDMA channel.



**Figure 6 Spread Spectrum Channel**

<sup>7</sup> This is actually an oversimplification since the Maximum Useable Frequency (MUF) varies greatly during the course of the day and even over the course of the 11 year sunspot cycle.

<sup>8</sup> This varies greatly with the height of the antenna. Commercial stations are almost always placed on very tall structures or mountain tops to assure a wide coverage area.

The *background noise* component is the normal ambient RF noise from natural background radiation. *External interference* is the interference from other stations and, *other cell interference* refers to interference that exists in a cellular communications network where spread spectrum is used.

## SPREAD SPECTRUM

Spread spectrum<sup>9</sup> is a technology for spreading the desired information signal, hereafter called the data signal, over a larger portion of the band than would normally be required to adequately transmit that information. Spreading a signal over a bandwidth in excess of what is required may seem counter intuitive to good efficient use of the spectrum. However, there are two reasons why spread spectrum is a viable alternative. First, many stations share the spectrum simultaneously. Second, the power used by each station is much lower than would normally be used by a narrowband station. Power reduction substantially extends the useful life of energy limited battery based systems. More important is the biological hazard reduction. While the level of the danger caused by RF radiation may be argued, there is little argument that less radiation is better.

Spreading is accomplished by modulo-2 addition of the data signal with the **spreading sequence**, also called the **spreading code**. The spreading sequence is a pseudo-noise (PN) code that has a bit rate that is much greater than the data signal rate. The result of this process is that the energy is spread over a wide frequency spectrum. The amount the information signal is spread is referred to as the **processing gain** or **spreading factor**. The relationship is shown as:

$$G_p = B_t / B_i$$

where:

$G_p$  = is the processing gain

$B_t$  = transmission bandwidth

$B_i$  = information bandwidth

### Equation 4 Processor Gain Relationship

Let's assume that 9.6 Kbps represents the data signal we wish to spread. If we spread the signal over 1.2288 MHz, we have a **processing gain** of 128 or 21 dB. Each bit of the PN sequence is referred to as a **chip**, and the rate of the sequence is called the **chip rate** expressed in chips per second (cps). In our example, the chipping rate is 1.2288 Mcps.

Spreading factors vary greatly. There is no theoretical limit. In fact, code sequences as short as 11 to as high as  $2^{29} - 1$  have been used. However, in practical commercial applications, values vary from 20 to 254.

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<sup>9</sup> Although spread spectrum may seem to be a state-of-the-art technology, in point of fact, the original idea was developed in 1940 by Hedy Lamarr, the actress. A patent was issued in 1942 to Ms. Lamarr and George Antheil whom she turned to, to help perfect the concept. The first use of spread spectrum was in 1962 when Sylvania installed equipment on ships during the Cuban missile crisis. (Source: Newton's Telecom Dictionary, Flatiron Publishing, Inc. 9th edition, 1995).

CDMA is just one of several spreading methods. Spreading codes and their characteristics result in substantially different transmission characteristics and spectrum use. The major advantages of spread spectrum are summarized in Table 3.

**Table 3 Advantages of Spread Spectrum**

- Resistant to interference, both intentional and non-intentional. In fact, this was the primary reason for its development. It was intended as a military application to overcome eavesdropping and jamming during World War II, although it was never deployed during that period.
- Relatively immune to multipath distortion. In fact, multipath signals can aid rather than hinder communication when the multipath signals can be combined.
- Spread spectrum provides privacy. Although this should not be confused with real security since eavesdropping is possible. However, spread spectrum requires significant expertise and fairly sophisticated equipment to demodulate.
- Spread spectrum provides low power spectral density. The information is spread over a large frequency range which reduces the common noise floor and therefore interference to other users.
- The spread spectrum signal can coexist with narrowband signals. This is possible since spread spectrum signals add only slightly to an increase in the noise floor and thus do not severely impact narrowband receivers.

Figure 7 compares narrowband and spread spectrum signals. Note that the narrowband signal has a much higher power spectral density but requires less bandwidth. Conversely, a spread spectrum signal requires more bandwidth, but has a much lower power spectral density.

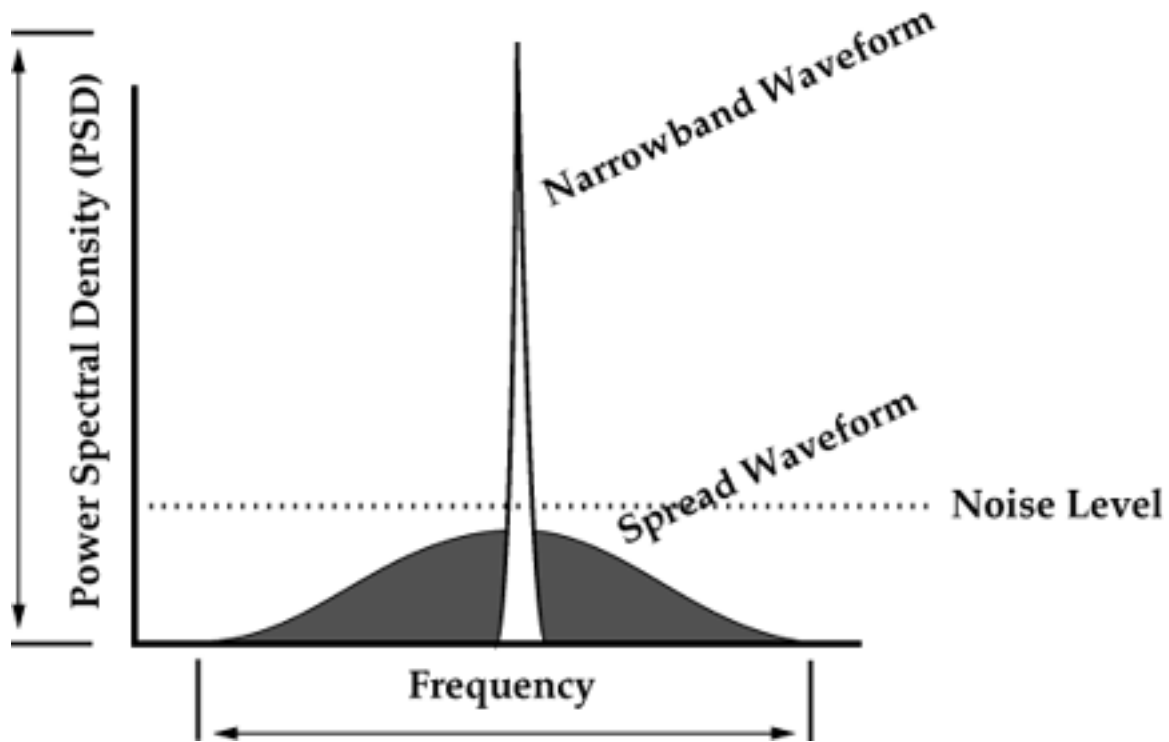


Figure 7 Spread Spectrum vs. Narrow Band Signal<sup>10</sup>

Spread spectrum systems are interference resistant since the receiver listens to a wide bandwidth with a prescribed code sequence. During demodulation, the **correlation receiver**, de-spreads incoming signals resulting in interfering signals also being spread. The ability of a correlation receiver to enhance the spread spectrum signal while reducing the narrowband jamming signal is shown in Figure 8.

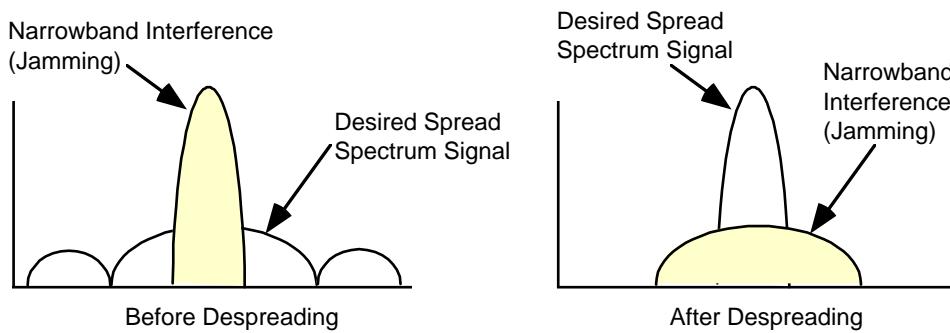


Figure 8 Interference Resistant

The spread spectrum receiver is effectively integrating all signals over a wide bandwidth to recover the desired spread spectrum signal. This integration process has the affect of reducing

<sup>10</sup> Source: Spread Spectrum, web page <http://www.tapr.org/ss/qexss.html>

the unwanted narrowband signal while the desired spread spectrum signal is enhanced. This immunity to jamming is a side benefit to the technology.

In the above discussion, we assumed that the interfering signal is a man made jamming signal. However, we can look at noise also as an interfering signal, albeit a wide bandwidth signal. Spread spectrum exhibits immunity to noise due to **processing gain**. Commercial systems offer processing gains in the range of 10 to 20 dB. The significance of this processing gain is that a spread spectrum system can actually function with a negative signal to noise ratio, since the processing gain of the system counteracts the poor signal to noise ratio.

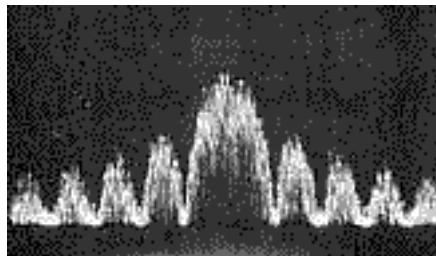
It is important to note that as additional spread spectrum users are added to a channel, the noise floor is raised slowly. For this reason, spread spectrum systems are said to have a **soft limit** to the number of users. As the number of users is increased, the system degrades gracefully rather than abruptly as in conventional communication systems. The only hard limit is the number of spreading codes. When all spreading codes have been used, the system cannot support additional users.

Having shown the characteristics of spread spectrum and its advantages, let's look at some techniques that are presently in use. **Direct Sequence (DS)** and **Frequency Hopping (FH)** are some of the more popular spread spectrum techniques. Other, less used, methods include **Time Hopping** and **Pulsed (Chirp)** systems.

### Direct Sequence Systems

Direct sequence spread spectrum (DSSS) is the most popular form of spread spectrum communication. The technique is to modulate the data signal with the spreading code (PN code sequence) using modulo-2 addition. The PN code has a fixed and relatively short length and repeats itself.

Figure 9 shows a DSSS signal as displayed by a spectrum analyzer.



**Figure 9 Spread Spectrum Photo of a DSSS signal<sup>11</sup>**

When an RF carrier is modulated with a PN code, the resultant signal has its main lobe centered at the original carrier frequency with a bandwidth of twice the chipping rate. Each of the side lobes has a null-to-null bandwidth equal to the chipping rate. The spreading method, PN code, and the modulation technique all play a major role in the resultant spectrum used.

<sup>11</sup> Source: <http://sss-mag.com/ss.html>, *The ABCs of Spread Spectrum*.

Inherent in a DSSS system is what is referred to as the **near-far problem**. This occurs when a user is located near the receiver and another located far from the receiving point. The result is a large disparity in signal strength received between the near and far stations. The near transmitter can totally negate the benefits of spread spectrum since it works by assuming that all stations are received at an equal power level. Spread spectrum can cope with narrow band signals, but it cannot easily cope with strong wideband signals (e.g., spread spectrum signal).

To counteract the affects of the near-far problem, a means to control the received power must be implemented. This process is called **power control**. A dynamic power range of 80 dB is not uncommon which allows power control from a few watts to less than a microwatt in a typical cellular application.

Equally important is the speed with which the power control algorithm can be controlled. A slow moving user (e.g., walking) is fairly easy to power control. However, high speed users (65 mph vehicles) move through environments very quickly. In these cases power control becomes more difficult. In fact, in quickly changing environments, power may not be able to compensate which results in errors. The errors must then be compensated for by other elements of the system. The interleaver, which we have previously discussed, is very helpful in mitigating the deleterious affects of very short fads.

### Frequency Hopping Systems

Spread spectrum signals can also be generated by frequency hopping (FH). The frequency changes (hops) in step with the PN code sequence. The transmitted signal is moved many times per second by the code sequence. The receiver, who also has a copy of the spreading code, moves (listens) in step with the transmitted signal. Note that this is different than a direct sequence system where the receiver listens to the entire bandwidth simultaneously.

Figure 10 shows an example of a Frequency Hopping Spread Spectrum signal on a spectrum analyzer. Note that the amplitude of the transmitted signals are equal which is significantly different than a DSSS generated signal.



**Figure 10 Spread Spectrum Photo of a Frequency Hopping signal<sup>12</sup>**

Figure 11 shows a FH signal again, but adds the missing parameter of time. Note again that the amplitude of the signal is constant as it hops between frequencies in time.

<sup>12</sup> Source: <http://sss-mag.com/ss.html>, *The ABCs of Spread Spectrum*.

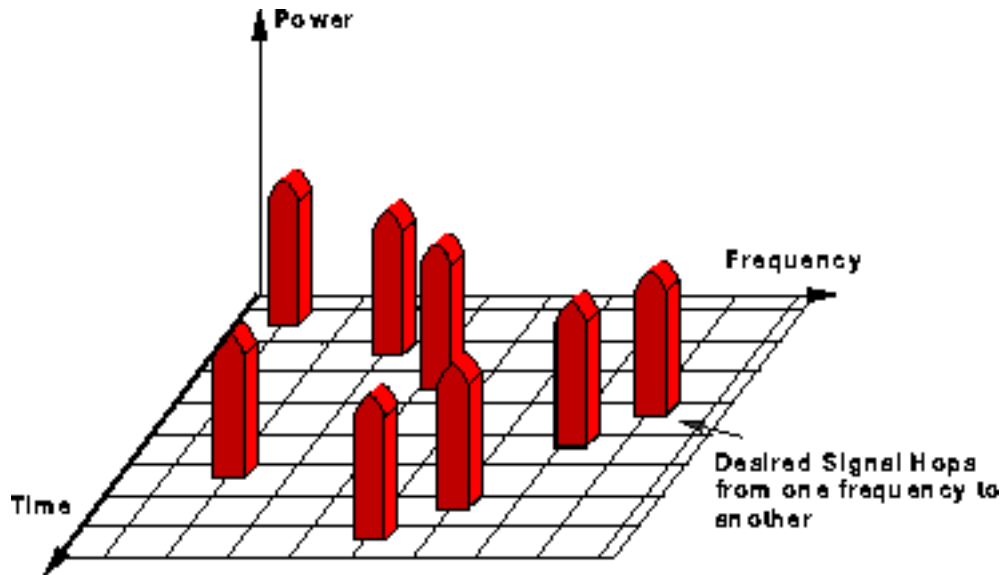


Figure 11 Frequency Hopping<sup>13</sup>

### Time Hopping Systems

While frequency hopping is performed in the frequency domain, time hopping is performed in the time domain. In time hopping systems, the period and duty cycle<sup>14</sup> of the RF carrier is modified under the control of the PN code. Each burst consists of  $n$  bits of data and the exact time each burst is transmitted is determined by the PN code.

<sup>13</sup> Source: Jack Glas Phd student, Delft University of Technology, Department of Electrical Engineering, Delft, The Netherlands. Available at <http://cas.et.tudelft.nl/~glas>. Reproduced with permission from author.

<sup>14</sup> Duty cycle is the term given to the ratio expressed in percent of on-time to the time of one period. For example, if a signal is on for 1 second and off for 9 second, it is said to have a duty cycle of 10%.

## Pulsed Systems

In a pulsed FM spread spectrum system, sometimes called a **chirp** system, an RF carrier is modulated with a fixed period and fixed duty cycle sequence. The carrier frequency is frequency modulated causing spreading of the carrier. The pattern of the frequency modulation depends upon the PN code. These systems are typically employed only in radar systems and rarely found in commercial applications.

## PN SEQUENCES

In each of the methods discussed, the spreading code is an integral part of the system and its importance cannot be overemphasized. How a PN code is generated and its characteristics are a branch of spread spectrum all by itself. Simplistically, any sequence can be used to spread the data signal. In practice, great care must be exercised in its selection.

PN codes are chip sequences that have **noise-like** properties. They may be **polar** (-1 and +1) or **non-polar** (0 and 1). It is the noise-like property that is responsible for the low-correlation among codes. Table 4 shows important characteristics of a good PN code.

**Table 4 Characteristics of a Good PN Code**

- Sequences must be built from 2-leveled numbers (e.g., 0 and 1 or -1 and +1).
- Codes should have 1 chip autocorrelation peak to enable code-synchronization.
- Codes must have a low cross-correlation value. This refers to the similarity between two signals. The degree of likeness is sometimes expressed as a value between 0 (perfect match, undesirable) and 1 (no match, very desirable). Low cross-correlation translates to increased channel capacity (e.g., more users).
- Codes should be balanced, the difference between ones and zeros in the code may only be 1. This characteristic provides good spectral density properties since the code is then similar to random noise.

Codes that meet one or more of the above criterion are: **Walsh-Hadamard**, **M-sequences**, **Gold**, **Four-phase**, and **Kasami** codes. We will limit our discussion to M-sequence (also called M-ary) and Walsh-Hadamard codes.

## Walsh-Hadamard Code Generation

Walsh-Hadamard, hereafter referred to simply as Walsh codes, can be thought of as a matrix. Table 5 shows a typical matrix of Walsh chips. Although any length code can be generated, we limit ourselves to a 64 bit Walsh code matrix. In the example, when a user needs a spreading code, one of the unused codes is selected. A Walsh index points to a Walsh sequence that

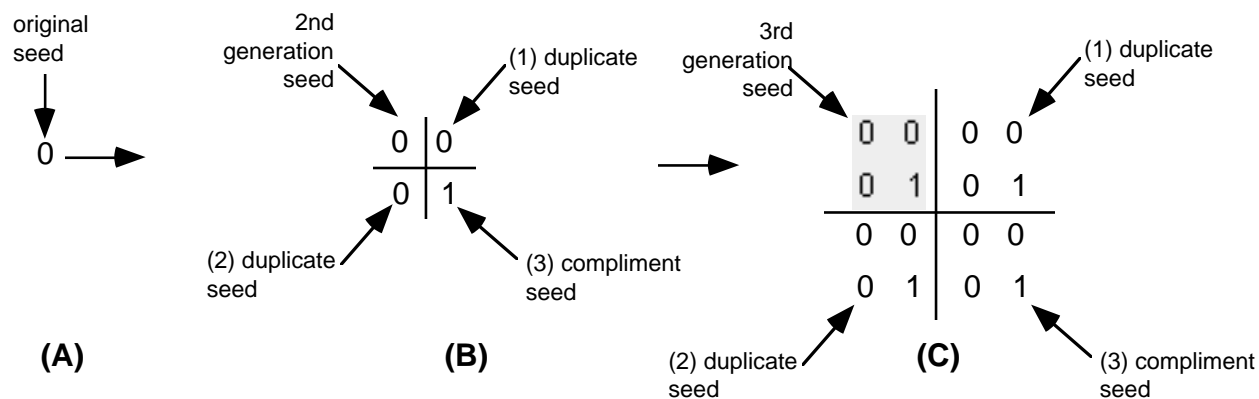
serves as the user's unique spreading code. Note that in this example the processor gain is 64, since the length of the spreading code is 64 bits.

**Table 5 Walsh Code Matrix Example**

Walsh Chip within a Walsh Function

	023	067	091	1043	1589	1723	2067	0001	1440	0989	0231	1645	0989	0231	0000
1	001	000	001	000	001	000	000	000	000	000	000	000	001	000	000
2	001	010	011	010	001	011	011	011	011	011	011	011	011	011	001
3	100	100	100	100	110	110	110	110	110	110	110	110	110	110	100
4	001	010	010	010	001	010	001	010	001	010	001	010	001	010	001
5	011	000	001	010	011	000	011	000	011	000	011	000	011	000	011
6	010	000	000	001	010	000	001	010	000	001	010	000	001	010	000
7	010	010	001	001	010	010	001	001	010	010	001	001	010	010	001
8	001	001	010	010	001	001	010	010	001	001	010	010	001	001	010
9	011	011	000	000	011	011	000	000	011	011	000	000	011	011	000
10	010	010	001	001	010	010	001	001	010	010	001	001	010	010	001
11	001	000	000	001	001	1000	1000	001	011	011	1000	1000	001	011	1000
12	110	110	110	110	110	110	110	110	110	110	110	110	110	110	110
13	001	001	001	001	010	010	010	010	001	001	010	010	001	010	001
14	011	011	011	011	1000	1000	1000	1000	011	011	1000	1000	011	011	1000
15	110	110	110	110	001	001	001	001	010	010	010	010	001	001	010
16	001	001	010	010	001	001	010	010	001	001	010	010	001	001	010
17	011	011	000	000	011	011	000	000	011	011	000	000	011	011	000
18	010	010	001	001	010	010	001	001	010	010	001	001	010	010	001
19	001	000	000	001	001	1000	1000	001	011	011	1000	1000	001	011	1000
20	110	110	110	110	110	110	110	110	110	110	110	110	110	110	110
21	001	001	001	001	010	010	010	010	001	001	010	010	001	001	010
22	011	011	011	011	1000	1000	1000	1000	011	011	1000	1000	011	011	1000
23	110	110	110	110	001	001	001	001	010	010	010	010	001	001	010
24	001	001	010	010	001	001	010	010	001	001	010	010	001	001	010
25	011	011	000	000	011	011	000	000	011	011	000	000	011	011	000
26	010	010	001	001	010	010	001	001	010	010	001	001	010	010	001
27	001	000	000	001	001	1000	1000	001	011	011	1000	1000	001	011	1000
28	110	110	110	110	110	110	110	110	110	110	110	110	110	110	110
29	001	001	001	001	010	010	010	010	001	001	010	010	001	001	010
30	011	011	011	011	1000	1000	1000	1000	011	011	1000	1000	011	011	1000
31	110	110	110	110	001	001	001	001	010	010	010	010	001	001	010
32	001	001	010	010	001	001	010	010	001	001	010	010	001	001	010
33	011	011	000	000	011	011	000	000	011	011	000	000	011	011	000
34	010	010	001	001	010	010	001	001	010	010	001	001	010	010	001
35	001	000	000	001	001	1000	1000	001	011	011	1000	1000	001	011	1000
36	110	110	110	110	110	110	110	110	110	110	110	110	110	110	110
37	001	001	001	001	010	010	010	010	001	001	010	010	001	001	010
38	011	011	011	011	1000	1000	1000	1000	011	011	1000	1000	011	011	1000
39	110	110	110	110	001	001	001	001	010	010	010	010	001	001	010
40	001	001	010	010	001	001	010	010	001	001	010	010	001	001	010
41	011	011	000	000	011	011	000	000	011	011	000	000	011	011	000
42	010	010	001	001	010	010	001	001	010	010	001	001	010	010	001
43	001	000	000	001	001	1000	1000	001	011	011	1000	1000	001	011	1000
44	110	110	110	110	110	110	110	110	110	110	110	110	110	110	110
45	001	001	001	001	010	010	010	010	001	001	010	010	001	001	010
46	011	011	011	011	1000	1000	1000	1000	011	011	1000	1000	011	011	1000
47	110	110	110	110	001	001	001	001	010	010	010	010	001	001	010
48	001	001	010	010	001	001	010	010	001	001	010	010	001	001	010
49	011	011	000	000	011	011	000	000	011	011	000	000	011	011	000
50	010	010	001	001	010	010	001	001	010	010	001	001	010	010	001
51	001	000	000	001	001	1000	1000	001	011	011	1000	1000	001	011	1000
52	110	110	110	110	110	110	110	110	110	110	110	110	110	110	110
53	001	001	001	001	010	010	010	010	001	001	010	010	001	001	010
54	011	011	011	011	1000	1000	1000	1000	011	011	1000	1000	011	011	1000
55	110	110	110	110	001	001	001	001	010	010	010	010	001	001	010
56	001	001	010	010	001	001	010	010	001	001	010	010	001	001	010
57	011	011	000	000	011	011	000	000	011	011	000	000	011	011	000
58	010	010	001	001	010	010	001	001	010	010	001	001	010	010	001
59	001	000	000	001	001	1000	1000	001	011	011	1000	1000	001	011	1000
60	110	110	110	110	110	110	110	110	110	110	110	110	110	110	110
61	001	001	001	001	010	010	010	010	001	001	010	010	001	001	010
62	011	011	011	011	1000	1000	1000	1000	011	011	1000	1000	011	011	1000
63	110	110	110	110	001	001	001	001	010	010	010	010	001	001	010
64	001	001	010	010	001	001	010	010	001	001	010	010	001	001	010

To understand how the Walsh table is generated, let's look at Figure 12.

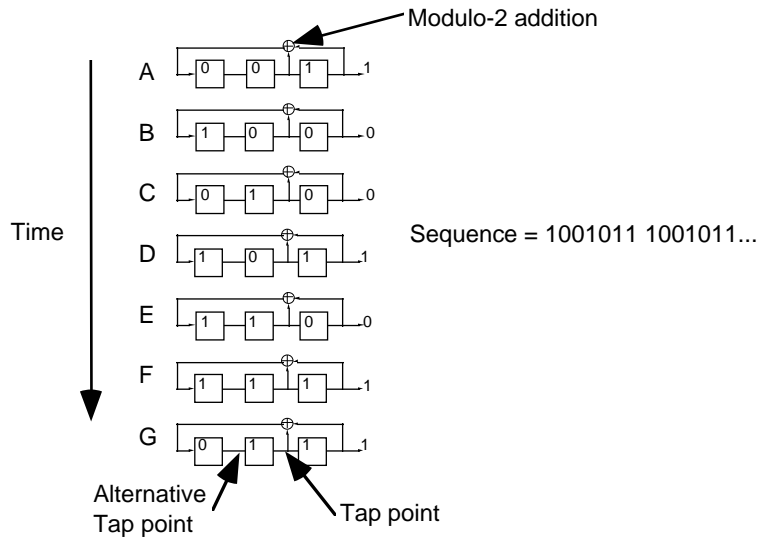


**Figure 12 Walsh-Hadamard PN Code Generation**

Assume we start with a seed value of zero as shown in (A). The seed is duplicated horizontally and vertically, and the complement of the seed becomes the diagonal value (B). This new mini-matrix becomes the new seed for the next iteration. Again the process of duplication and complementing is applied to the new seed, the results are shown in (C). This process continues until we have developed the number of codes required.

### M-Sequence Code Generation

A second method used for PN code generation makes use of a **linear shift register (LSR)**. Figure 13 shows a three (3) bit shift register which moves through 7 states before the sequence is repeated. In the initial state (A), the output of the shift register is 1. During the next clock cycle, bits are shifted, modulo-2 addition is performed and the output is 0 (B). The process continues through states C to G yielding a spreading code of 1001011. In this example, the code length is unrealistically short. In practice, lengths such as 63 (7 bit LSR) or 127 (8 bit LSR) are used.



**Figure 13 PN Code Generation**

In this 3 bit LSR example, note there are two points to tap off the value that will be used for the modulo-2 addition. The tap point may be varied according to the desired polynomial which affects the characteristics of the resulting sequence. Assuming the length of the shift-register is  $n$ , the period can be described as shown in Equation 5.

$$N_{ds} = 2^n - 1$$

**Equation 5 LSR Relationship**

A cursory inspection of the relationship shows that the output from a LSR always contains an odd number of bits. In commercial systems, this sometimes causes problems and an additional bit is added to simplify timing. Without further explanation we move on, however, the tap point, the length of the LSR, and other factors of the sequence play a major role in the final spread spectrum signal and careful consideration is necessary.

## Walsh-Hadamard vs. M-Sequence

Walsh codes also have limitations, they do not have a single narrow autocorrelation peak, one of the criterion for a good PN code sequence. In addition, spreading is limited to a discrete number of frequency components as shown in Figure 14.

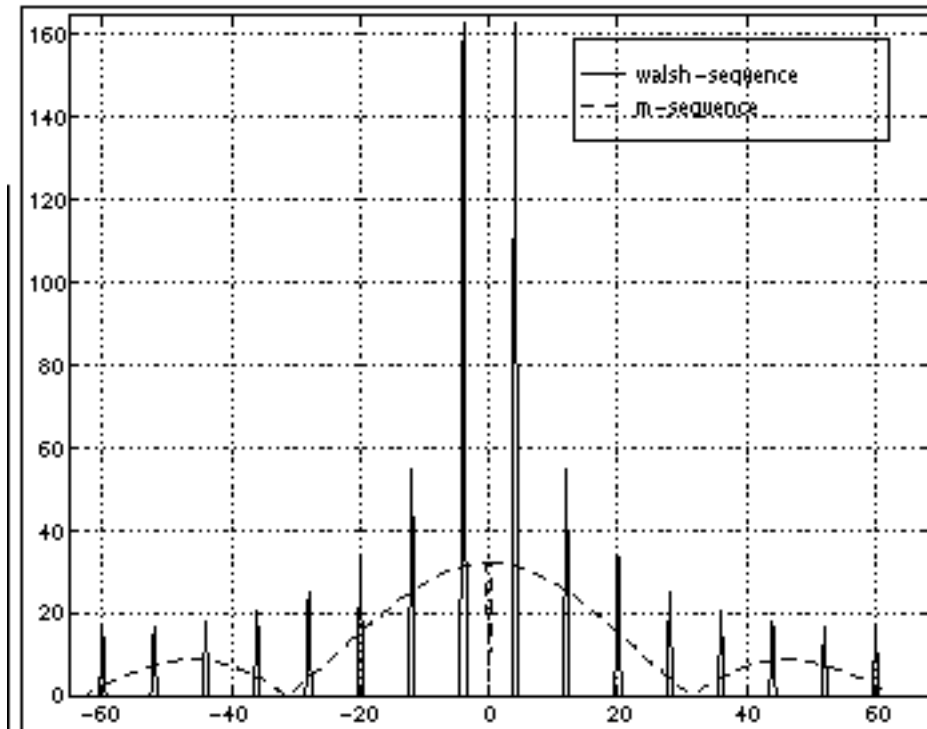


Figure 14 Walsh-Hadamard and M-Sequence Compared<sup>15</sup>

Since the LSR produces an odd number of bits, it is not possible for the number of 0 states to equal the number of 1 states. Recall that one of the desired traits of a good PN code requires that zeros and ones be equal. Despite this limitation there are still good reasons to use a LSR to generator PN codes. For example, M-ary codes exhibit fewer peaks as compared to Walsh codes and spread the data signal more smoothly over a wider band of frequencies.

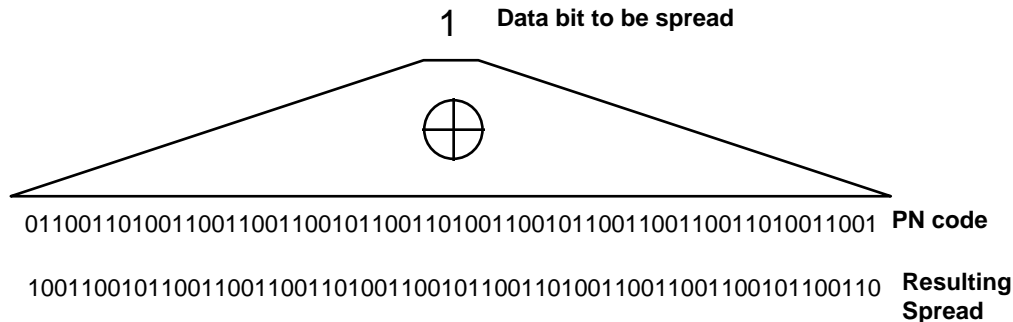
For theoretical and practical reasons, both codes are viable solutions to the generation of PN codes despite their less than perfect characteristics.

## Spreading

Whether we use Walsh, M-ary, or other methods for the generation of the PN code, the spreading of the data signal is accomplished in the same manner. Specifically, we add

<sup>15</sup> Source: Jack Glas Ph.D. student, Delft University of Technology, Department of Electrical Engineering, Delft, The Netherlands. Available at <http://cas.et.tudelft.nl/~glas>. Graph developed by using DFT and computer program MatLab. Reproduced with permission from author.

(modulo-2 addition) the PN code with the data signal to generate the spread signal. Figure 15 shows how a data bit (1) is spread using Walsh code index 59 from the Walsh table previously developed. The resulting data stream from the operation is shown in the lower portion of the figure. It should be easy to see from our discussion that the processing gain is 64. Although we are limiting our discussion to the generation of spread spectrum signals, it is appropriate to note that the information is recovered at the receiver by modulo-2 adding the received signal with a locally generated replica of the PN code sequence.



**Figure 15 Spreading**

## MODULATION

If we refer back to the generic spread spectrum block diagram (Figure 1), we see that we are now ready to modulate the digitally spread signal with an RF carrier so that it can be transmitted. There are a plethora of modulation techniques. Besides everyday techniques such as AM and FM, there are more esoteric methods.

To understand why some modulation techniques are used over others, it is useful to start at the very beginning of digital communication, Morse Code. Morse code is a combination of tones and the absences of tones. Electronic circuits such as **phase locked loops** (PLL) can easily lock to a signal (tone), however, the absence of a tone is more difficult to lock to. For this reason, two states are most often used to represent digital information (0 and 1) and thus to increase reliability of the data.

Table 6 shows some modulation techniques that are used for the transmission of digital information.

**Table 6 Modulation Techniques**

<i>Item</i>	<i>Description</i>
FSK	Frequency Shift Keying in which a signal changes between two frequencies.
AFSK	Audio Frequency Shift Keying is identical to FSK with the difference being the way in which the two frequencies are generated.
PSK	Phase Shift Keying changes the phase of a signal against a specified reference.
BPSK	Binary Phase Shift Keying
DPSK	Differential Binary Phase Shift Keying changes the phase with respect to succeeding pulses in the same data stream.
QPSK	Quadrature Phase Shift Keying also call Quad (4) Phase Shift Keying.
OQPSK	Offset Quadrature Phase Shift Keying
C4FM	Uses a Nyquist Raised Cosine Filter cascaded with shaping filter, cascade with a frequency modulator (FM)
CQPSK	Consists of a table look-up, the two outputs of which (I and Q) are Nyquist filtered and then amplitude modulated, in phase and quadrature phase, before summing. The information bits are processed by the look-up table to yield a 5-level I signal and a 5-level Q signal. The I and Q signals are filtered with the Nyquist Raised Cosine Filter previously described. The I signal is then multiplied by the carrier and the Q signal is multiplied by the carrier after it has been delayed by 90 degrees. The modulated I and Q carriers are then summed together to yield the modulator output
16QAM	16 level Quadrature Amplitude Modulation - this is the modulation technique or similar form is used in every 28.8 Kbps modem.

Two states may be achieved using **amplitude modulation** (AM) where two amplitude levels represents digital values (0 and 1). However, it is a poor solution since in a wireless environment, changes in propagation normally cause changes in amplitude. These unwanted variations in amplitude would erroneously be interpreted as data. Therefore, AM is not a viable solution for a robust communication system.

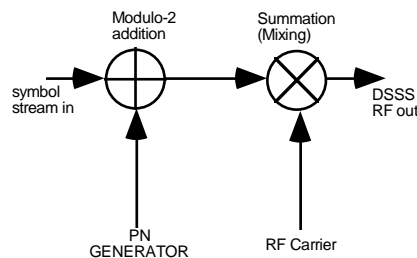
**Frequency modulation** (FM) is also a poor solution since, as its name implies, the frequency is constantly changing making it difficult for an electronic circuit to lock to the frequency. This is particularly true of satellite communication where Doppler frequency shifts can be misinterpreted as part of the desired data.

We now move to a viable solution, **phase shift keying** (PSK). In this modulation scheme only the phase of a signal changes. Frequency and amplitude may vary slightly without causing errors. For this reason, PSK is an effective modulation technique; neither amplitude or

frequency variations affect demodulation. Numerous PSK methods are used, some of the more popular techniques are BPSK, QPSK, and OQPSK.

## BPSK

In **Binary Phase Shift Keying (BPSK)**, as its name implies, we shift a signal in phase between two levels. While we can select any phase shift, electronic circuits become more complex as the phase shift magnitude is reduced. BPSK circuits are normally designed to distinguish between the existence (e.g., 0) or non-existence (e.g., 1) of a particular phase. For practical systems, the phase differences are large to ease detection. Values of 0 and 180 degrees normally represent the two binary states.



**Figure 16 BPSK**

## QPSK

**Quadrature Phase Shift Keying (QPSK)** is much like BPSK, but the number of phase shifts is doubled. Each phase corresponds to two bits of information. Phase shifts of 0, 90, 180, and 270 degrees correspond to data of (0 0), (0 1), (1 0), and (1 1) respectively. Using a quadrature signal allows the bit rate to be doubled, while only slightly increasing complexity of the system.

It would appear that we could continue to increase the number of phase shifts in an effort to concentrate more and more information in the transmitted signal, unfortunately there is a limitation. The ability of a real world electronic circuit to reliably differentiate a large number of phases becomes the limiting factor. QPSK (4 phases) and 8PSK (8 phases) are the generally accepted limit.

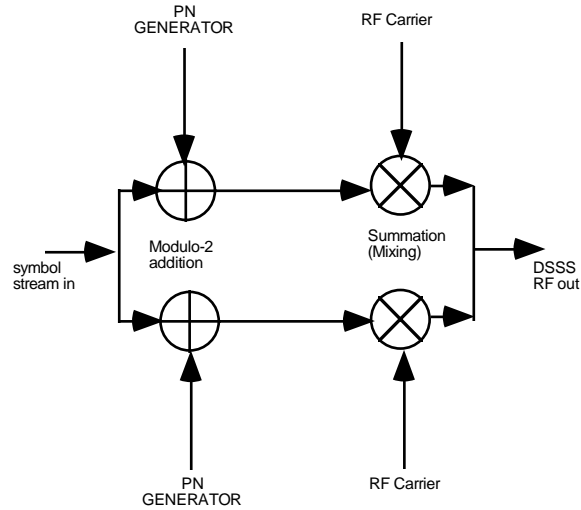


Figure 17 QPSK

### OQPSK

**Offset Quadrature Phase Shift Keying** is a slight variation of QPSK. The major difference being that in OQPSK one of the two quadrature signals is **offset in time**. The offset varies with system implementation, but is often in the order of a half chip time. For a chipping rate of 1.2288 MHz (chip rate = 814 ns), an offset may be on the order of 407 ns. The reason for this offset is strictly practical. By offsetting the signal, the power envelop is more constant making it more friendly to power amplifiers.

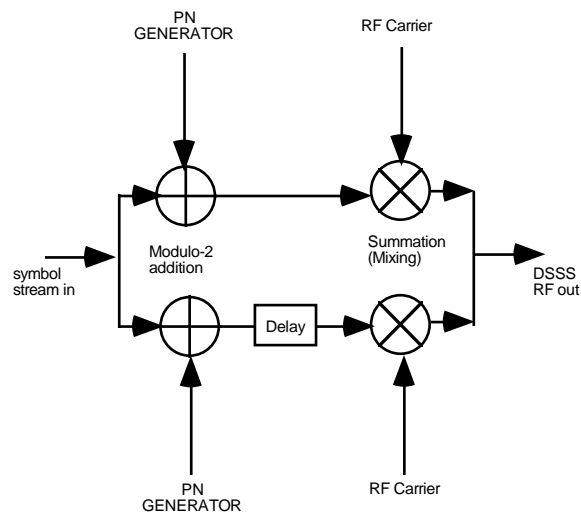


Figure 18 OQPSK

## CONCLUSION

The RF spectrum is a valuable and limited resource that must be carefully managed. The solution to effectively and efficiently using this resource lies in allowing multiple users to access the medium. Toward that end, several methods are presently in widespread use or under development. Unfortunately, there is no clear method that is superior to all others in all circumstances, each has its own advantages and disadvantages. However, there is agreement that by digitizing the information, more complex methods for communication can be developed.

We have stepped through each of the important elements of a wireless digital communication system. The codec, vocoder, encoder, interleaver, the PN generator, and RF modulator all play a key role in preparing the data before it enters the harsh wireless world. It is the careful attention to optimizing each of these elements that allows us to increase channel capacity and approach the Shannon limit.

## SPREAD SPECTRUM TALKS AND PRESENTATIONS

The following are Real Audio presentations available from [http://www.tapr.org/ss/ss\\_audio.html](http://www.tapr.org/ss/ss_audio.html). This page provides many additional links to other audio presentations.



*Spread Spectrum an Overview*, Greg Jones, WD5IVD, and Tom McDermott, N5EG from TPRS Digital Forum, HamCom (Arlington, Texas) 1996



*Ham Radio and More Show: 5/26/96*, Guest: Dewayne Hendricks, WA8DZP, CEO Warp Speed Imagineering Topic: Spread Spectrum Communications National Hour



*Ham Radio and More Show: 5/26/96*, Guest: Dewayne Hendricks, WA8DZP, CEO Warp Speed Imagineering Topic: Spread Spectrum Communications Local Hour



*Spread Spectrum Technology and current issues in Amateur Radio* Phil Karn, KA9Q and Steve Bible, N7HPR from TAPR Digital Forum, Dayton Hamvention 1996



*Ham Radio and More Show 6/13/93* Guest: Jack Tiley, N7RWJ (on Spread Spectrum Communications) National Hour

## SPREAD SPECTRUM WEB PAGES

1. URLs for more information on Spread Spectrum  
[http://www.cdg.org/a\\_ross/index.html/](http://www.cdg.org/a_ross/index.html/)  
<http://www.tapr.org/ss/smith/smith.html#contents/>  
<http://olt.et.tudelft.nl/~glas/ssc/techn/techniques.html/>
2. URLs for more information on telecommunications in general  
<http://www.qualcomm.com/people/pkarn/voicedemo/index.html/>

## ANNOTATED BIBLIOGRAPHY

Bible, Steve, N7HPR. "*Spread Spectrum - It's not just for breakfast anymore!*" QEX magazine. The American Radio Relay League. Newington, CT. 1995.

The paper is intend for amateur radio users who have a technical background, but not in spread spectrum communication. It discusses the basic types of spreading such as frequency hopping, and direct sequence.

Fleeter, R. G. Huffman, "*Satellite Radio*", Third in a three part series, New Space Newsletter, August 1994.

A down to earth article (no pun intened) on satellite communication. It explains in semi-technical terms some of the problems facing satellite communication and why some of the modes of operation are used and why others are not. For example, why PSK is used over conventional methods such as AM and FM is explained.

Hendricks, Dewayne, WA8DZP. *Spread Spectrum and the Amateur Radio Service - Recent Developments PSR #60 Fall 1995*. TAPR. Tucson, AZ. 1995.

The paper is a call to arms to the amateur radio service to experiment with spread spectrum technology. For decades, many commercial products have had the infancy in the amateur radio community. However, spread spectrum does not follow this rule. The commercial sector is embracing spread spectrum technology and many products are currently available for use. It is the author's intention to bring the subject of spread spectrum to the forefront in the hopes of challenging amateurs to experiment with spread spectrum.

Katz, R. H. "*Adaption and Mobility in Wireless Information Systems*," IEEE Personal Communications, pp. 6-17, First Quarter 1994.

The paper is a high level overview of the problems facing mobile communication. Also discussed is the fuel that drives the evolution, specifically, mobility which is considered a natural evolution of computing. Included are definitions such as ubiquitous, nomadic, and detachable computing, each being driven by a slightly different need or market, yet all require mobility. The paper also discusses the components that make up a wireless network such as the user terminal, the wireless link, the base station, network protocol.

Kohno, Ruji, Reuven Meidan, and Laurence B. Milstein. "*Spread Spectrum Access Methods for Wireless Communications*," IEEE Communications Magazine, pp. 58-67, Jan. 1995.

An excellent paper that provides both a low and high level description of spread spectrum technologies. The paper concentrates on two methods for spreading, Frequency Hopping (FH) and Direct Sequence CDMA. A comparison is made indicating the advantages and disadvantages of each.

Pickholtz, Raymond L., Donald L. Shilling, and Laurence B. Milstein. "*Theory of Spread-Spectrum Communications - A Tutorial*," IEEE Communications Magazine, pp. 855-884, May 1982.

Although the paper states it is a tutorial, it is for graduate level students and/or the telecommunication engineer. It provides a technical and mathematically rich discussion of spread spectrum. Topics include discussions on processing gain, and power spectral density. Much of the paper is devoted to the generation of PN (pseudo noise) codes which are the basis for spreading.

Shannon, Claude, "*A Mathematical Theory of Communication*", Bell System Technical Journal, Vol. 27, pp. 379-423 and 623-656, July and October, 1948.

The classic work in which Claude Elwood Shannon first proposed the Shannon limit which describes the relationship between channel capacity, bandwidth, and the signal to noise ratio.

Shepard, Timothy Jason, "*Decentralized Channel Management in Scaleable Multihop Spread-Spectrum Packet Radio Networks*" Phd thesis, Massachusetts Institute of Technology, MIT/LCS/TR-670, July 1995.

An excellent and very readable paper on the subject of spread spectrum packet radio networks. The study of the paper is a look at the problems of managing the transmissions of stations in a high density packet network. High density in this case refers to thousands of nodes within a relatively small area. The finding of the paper is that if traffic is limited to a few hops, then for a large system the techniques present in the paper are superior to time division multiplexing of a clear channel.

Smith, Darryl, VK2TDS "*A Spread Spectrum Packet Radio Network*" Report submitted in Partial Fulfillment of the Requirements for the Degree of Bachelor of Engineering (UTS) in Electrical Engineering. Academic Supervisor: A/Prof. Sam Reisenfeld. UNIVERSITY OF TECHNOLOGY SYDNEY, SCHOOL OF ELECTRICAL ENGINEERING 2, 1995.

An undergraduate level thesis on Spread Spectrum and amateur packet radio. The paper concentrates on a project to build a spread spectrum packet radio station. It describes the problems and solutions found during the project. The author provides many quotes and references for further study. Although the outcome was not an actual working spread spectrum system, the paper was useful as a HOWTO for a single user to understand spread spectrum communication and how it may be used for amateur communication.

Viterbi, A. J., (1991). *Wireless Digital Communication: A View Based on Three Lessons Learned*. IEEE Communications Magazine, September 1991. Reprinted in *Multiple Access Communications: Foundations for Emerging Technologies*, Norman Abramson, editor. IEEE order no PC0287-3.

This paper is an overview of the significance of Shannon Theory, and specifically the three lessons that can be learned by examining the relevance of the theory. More specifically, the author shows how each of the three lessons have real world significance such as jamming in a military application and more recently satellite communication. The paper emphasizes that

digital communication provides advanced techniques for: multiple-user access, multiple cell-sites, multipath, and multiple media. The paper ends with indicating why CDMA is superior to other modulation techniques such as TDMA and FDMA. Specifically, the reason stated is that CDMA has learned from all three lessons that Shannon's limit shows, while the other modulation techniques have not.

## BIOGRAPHY



Richard Parry, holds a BS in Electrical Engineering from the University of Illinois, (Urbana, Illinois), an MBA from Northern Illinois University, (DeKalb, Illinois) and a MSCS from North Central College (Naperville, Illinois). He is currently attending the University of California San Diego where he is studying computer science. He is a licensed Professional Engineer (Texas) and has authored papers in various areas including: Wireless Packet Networks, Oxygen Monitoring Systems, Programmable Electronic Safety Systems, Computerized Security Systems, speech synthesis and recognition, management tools, and amateur radioteletype. He is a big fan of the Linux Operating System where he spends entirely too much time. Other interests include amateur radio and more recently satellite communication.