FEATURE

Wireless Technology Series: Part 3
An Overview of the Technology and Its Applications
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DIGITAL MODULATION TECHNIQUES AND SPREAD SPECTRUM

Before we can delve into spread spectrum we must first discuss some of the basics of digital modulation. In the last paper[6] we discussed amplitude and frequency modulation. Spread Spectrum was introduced with a brief historical background of its origin. In this paper we will show how these modulation techniques can be modified or enhanced to support data transmission.

DIGITAL MODULATION[1]

The field of "Data Transmission" is loaded with various modulation schemes. Most involve translation of data bits or patterns into a unique combination of phase, frequency or amplitude. Some of the more notable techniques are listed in Table 1.

Each of the modulation formats listed in Table 1 are suited to a specific application. In general, schemes where two or more bits are represented by a symbol (e.g. QAM, QPSK) require better signal to noise ratios (SNR) than two-level (binary) schemes for similar bit-error-rate (BER) performance. Additionally, in a wireless system, schemes that have more than two levels (m-ary) generally require greater power amplifier linearity. Most implementations of the modulation formats listed in Table 1 are synchronous. When data rates exceed 1200 bits/second or when the transmission medium is subject to non-ideal effects (e.g. fading or SNR < 25 dB) synchronous data transmission is preferred over asynchronous. Synchronous data transmission is characterized by the presence of a clock which is synchronous to the data. The clock is embedded in, and therefore recoverable from, the modulated signal.

Another important consideration in data transmission is bandwidth. A stream of data, composed of sharp "one to zero" and "zero to one" transitions, results in a spectrum rich in harmonic content that is not well suited to direct RF transmission. Hence, digital modulation formats that minimize bandwidth (BW) consumption are necessary. As implied earlier, digital modulation involves the mapping of changes in data states to changes in amplitude, frequency, phase, or some combination of the three. Entire families of modulation formats, categorized as continuous phase modulation (CPM) minimize BW consumption by smoothing phase discontinuities at state changes while the amplitude of the carrier envelope remains constant (i.e. phase modulation or frequency modulation).

Continuous Phase Modulation[4]

One of the simplest forms of constant envelope modulation is Binary Frequency Shift Keying (BFSK). This type of modulation is composed of two sinusoids $cos\omega_1(t)$ and $cos\omega_2(t)$ with one selected for a logic zero and the other for a logic one. An implementation of this type of BFSK system would appear as shown in Fig. 1. This type of BFSK is referred to as "discontinuous phase" or "non-coherent" FSK because there is no coherence between the phase of ω_1, ω_2 and the modulating signal (DATA SOURCE). CCITT standard V.21 (300 baud) is an example of non-coherent FSK ($f_1 = 1080$ Hz and $f_2 = 1750$ Hz). It has also been applied to other low data rate systems where bandwidth efficiency is not an issue.

An alternative method for generating FSK is to use a voltage controlled oscillator (VCO) or frequency modulator. The key aspect of the VCO is, for instantaneous frequency deviation proportional to the modulating signal $s(t)$, the phase must be proportional to the integral of the modulating signal. From Ref. 6 where FM was introduced

$$e(t) = A_C \cos\left(\omega_C t + K \int_0^t s(\tau)d\tau\right) \tag{1}$$

Here, $e(t)$ = modulated carrier, A_C = amplitude of unmodulated carrier, $\omega_C = 2\pi f_C$ = angular frequency of unmodulated carrier, $s(t)$ = modulating signal and K = constant of proportionality.

If the modulating signal $s(t)$ is binary data,

$$s(t) = \sum_{n=-\infty}^{+\infty} S_n r(t - nT) \tag{2}$$

where, $S_n = \pm 1$, according to bipolar data polarity (logic $1 = +1$, logic $0 = -1$) and $r(t)$ = rectangular pulse with amplitude $1/(2T)$ and duration T. Substituting Eq. (2) into Eq. (1) yields

Table 1—Modulation formats

MODULATION TECHNIQUE	COMMON ACRONYM
Frequency Shift Keying	**FSK**
Multi-level Frequency Shift Keying	**MFSK**
Continuous Phase Frequency Shift Keying	**CPFSK**
Minimum Shift Keying	**MSK**
Gaussian Minimum Shift Keying	**GMSK**
Tamed Frequency Modulation	**TFM**
Phase Shift Keying	**PSK**
Quadrature Phase Shift Keying	**QPSK**
Differential Quadrature Phase Shift Keying	**DQPSK**
$\pi/4$ Differential Quadrature Phase Shift Keying	**$\pi/4$ DQPSK**
Quadrature Amplitude Modulation	**QAM**

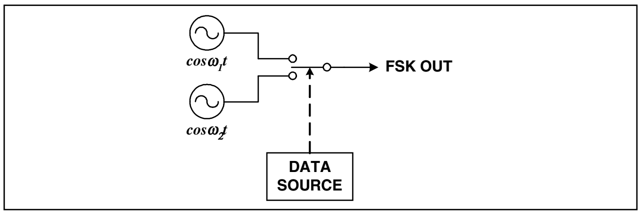

Fig. 1: Discontinuous phase BFSK modulator

$$e(t) = A_C \sum_{n=-\infty}^{+\infty} \cos\left[\omega_C t + KS_n \frac{1}{2T} t\right] \tag{3}$$

As a result, if the modulating signal (NRZ binary data) has no impulses, the modulated carrier $e(t)$ will not have phase discontinuities. In other words, injecting binary NRZ data directly into a VCO generates CPFSK.

Also introduced in Ref. 6 was the definition for modulation index in FM as the ratio of peak frequency deviation of the carrier to the frequency of the input signal. For data input, the modulation index becomes

$$m_{CPFSK} = \Delta f T \tag{4}$$

where, $\Delta f = |f_{LOGIC_1} - f_{LOGIC_0}|$ and T = symbol or bit period. Equation (3) can be rewritten in terms of $\boldsymbol{m}$ as

$$e(t) = A_C \sum_{n=-\infty}^{+\infty} \cos 2\pi\left(f_C + mS_n \frac{1}{2T}\right)t \tag{5}$$

An interesting case occurs when $m = 0.5$. Referring to Eq. (5), for $S_n = +1$, the frequency of the carrier is shifted higher to $f_{LOGIC_1} = f_C + (1/4T)$. When S_n is -1, the frequency of the carrier is shifted lower to $f_{LOGIC_0} = f_C - (1/4T)$. The difference between f_{LOGIC_1} and f_{LOGIC_0} is $(1/2T)$. In other words, for $m = 0.5$, the frequency separation between f_1 and f_2 is equal to half the bit rate. As a result, if f_1 and f_2 are orthogonal, this represents the "minimum" separation between f_1 and f_2, and is known as Minimum Shift Keying (MSK). This modulation scheme was first proposed by Doelz and Heald[2] and resulted in a US Patent, assigned to the Collins Radio Company. Figure 2 is a simplified block diagram for a MSK modulation system.

A further enhancement to this modulation technique is to apply a Gaussian filter to the NRZ data stream which smoothes the data transitions prior to being applied to the VCO. This modulation technique is known as Gaussian Minimum Shift Keying (GMSK).[3] GMSK is one of the more popular wireless digital modulation techniques because it is BW efficient yet relatively straight forward to implement.

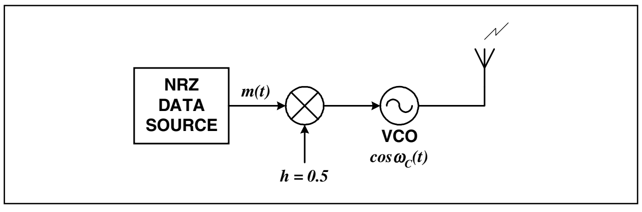

Fig. 2: MSK modulator

Thus far we have described two ways to generate one type of digital modulation. For modulation techniques with more than two phase states (e.g. QPSK) quadrature techniques must be used. Of course quadrature techniques can also be used for modulation techniques that only have two phase states as well. We will not go into the specifics of quadrature modulation techniques, however, the interested reader should refer to Refs. 1, 4 and 5 for a thorough explanation.

A modulation scheme is of little practical value if it can not be demodulated in an efficient manner. The definition of efficiency is somewhat dependent on the application—in general cost, size, and power consumption must be minimized while performance must be maximized. The performance of a demodulator can be quantified by looking at the signal-to-noise ratio (SNR) versus bit-error-rate (BER). However, SNR is generally considered as an inaccurate method for comparison of performance because of its dependence on noise BW. Unless all systems have identical BW it is difficult to make comparisons. A more accepted measure of performance is E_b/N_0 versus BER. E_b/N_0 is related to SNR as shown below,

$$\frac{E_b}{N_0} = \frac{S}{RN_0} = \left(\frac{S}{N}\right)\left(\frac{B_n}{R}\right) \tag{6}$$

where S = signal power, R = data rate in bits per second, N_0 = noise power spectral density (watts/Hz), E_b = energy per bit, $B_n N_0 = N$ = noise power and B_n = noise BW of IF filter.

For all of the modulation techniques mentioned in Table 1, the BER decreases with an increase in E_b/N_0. Where they differ is in the rate of decrease in BER at low E_b/N_0 ratios. In most cases those that perform well (low BER at low E_b/N_0) are more complex in implementation.

SPREAD SPECTRUM[5]

Spread spectrum is a modulation technique where bandwidth is sacrificed to gain signal-to-noise performance according to the well known expression for channel capacity.

$$C = W \log_2 (1 + S/N) \tag{7}$$

where C = channel capacity in bits, W = bandwidth in Hertz, S = signal power and N = noise power.

Hence, a narrow band signal can be spread across a wide bandwidth with lower peak power yet maintain equivalent performance.

Spread spectrum can deliver superior performance in the presence of narrowband noise because increasing the trans-

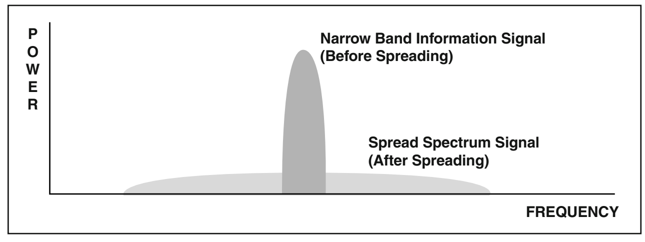

Fig. 3: Power versus frequency for spread spectrum

mitted signal bandwidth results in an increased probability that the received information will be correct. If total signal power is interpreted as the area under the spectral density curve, then signals with equivalent total power may have either a large signal power concentrated in a small bandwidth or a small signal power spread over a large bandwidth.

The performance improvement or Process Gain is quantified as

$$GP = \frac{BW_{RF}}{R_{INFO}}. \quad (8)$$

where BW_{RF} = RF bandwidth in Hertz and R_{INFO} = information rate in bits/second.

The two most ubiquitous approaches to spread spectrum are Direct Sequence Spread Spectrum (DSSS) and Frequency Hopping Spread Spectrum (FHSS). DSSS uses a pseudo random sequence for its modulating function. FHSS uses a pseudo random sequence to change the channel frequency of the radio.

As mentioned in Part 2 of this series,[6] spread spectrum was patented by Hedy Markey (Ms. Heddy Lamarr) and George Antheil in 1941 (US patent 2,292,387 "Secret Communication System"). It was developed by the military during the 50s under classified projects and saw first significant use for ship to ship communications in 1962 during the Cuban Missile Crisis. Commercial applications started to gain in popularity in the 1980s. Equatorial Communications of Mountain View, CA used DSSS for multiple access communications over synchronous satellite transponders.

Key to both DSSS and FHSS is the pseudo random noise (PN) codes used to spread the modulating signal. These PN codes can be generated by a linear feedback shift register (LFSR). A LFSR PN generator consists of a shift register in conjunction with the appropriate logic, which feeds back a logical combination of the state of two or more of its stages to its input. The output, and the contents of its "*n*" stages at any clock time, is a function of the outputs of the stages fed back at the proceeding sample time. Codes can typically be of length 7 to [(2^36)-1].

A PN code must meet the following constraints:

- The sequences must be built from 2-leveled numbers.
- The codes must have a sharp autocorrelation peak to enable code-synchronization.
- The codes must have a low cross-correlation value, the lower this cross-correlation, the more users allowed in the system.
- The codes should be "balanced": the difference between ones and zeros in the code may only be 1. This last requirement stands for good spectral density properties (equally spreading the energy over the whole frequency-band).

Figure 4 shows simplified block diagrams of DSSS and FHSS modulators. Notice both use PN code generators.

In DSSS, a PN code exists in units called chips, these chips can have 2 values: −1/1 (polar) or 0/1 (non-polar). As we combine every data symbol with a complete PN code, the DS processing gain is equal to the code-length.

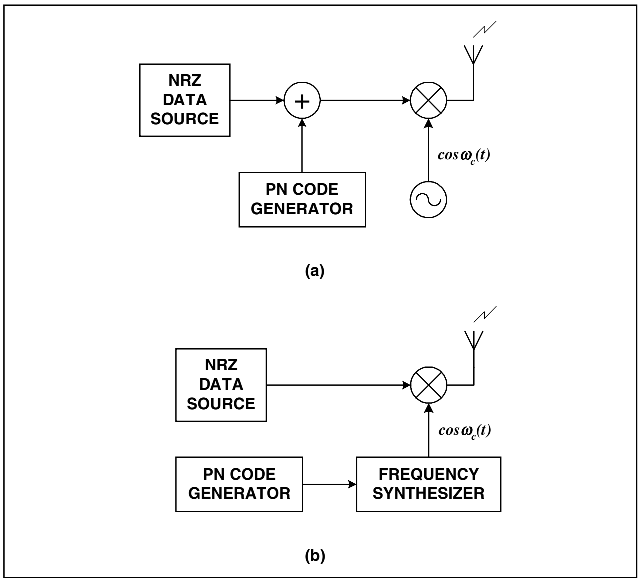

Fig. 4: Simplified block diagrams of (a) DSSS and (b) FHSS modulators

Codes that can be found in practical DSSS systems are: Walsh-Hadamard codes, M-sequences, Gold-codes and Kasami-codes. These code sets can be roughly divided into two classes: orthogonal codes and non-orthogonal codes. Walsh sequences fall in the first category, while the other group contains the so-called shift-register sequences.

Figure 5 illustrates the process of combining a data signal with a PN code to generate a DSSS coded signal.

In FHSS, the carrier frequency is altered ("hops") according to a PN code. In this way the bandwidth is increased by a factor proportional to the length of the PN code (the discrete channel frequencies must be non-overlapping).

The process of frequency hopping is illustrated in Fig. 6. A disadvantage of FHSS when compared to DSSS is that obtaining a high processing-gain is dependent on the ability of the frequency synthesizer to change carrier frequencies rapidly—the faster the "hopping-rate" the higher the processing gain.

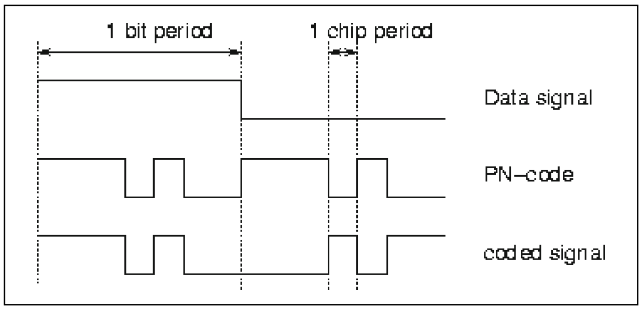

Fig. 5: Generation of a DSSS coded signal from a PN code

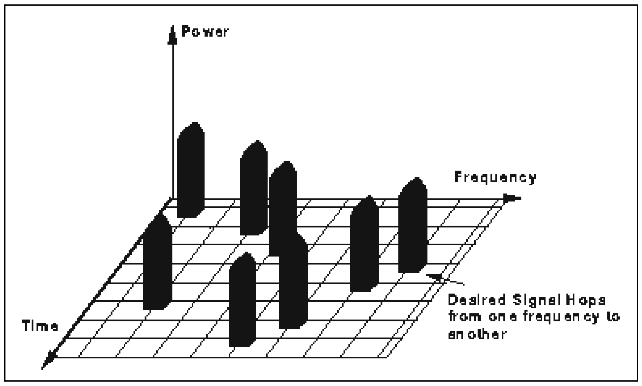

Fig. 6: FHSS in time-frequency domain

Spread Spectrum Bands

The FCC allows the unlicensed use of SS technology in three radio bands,

- 902-928 MHz,
- 2400-2483.5 MHz
- 5752.5-5850 MHz

These bands are also known as the Instrumentation, Scientific and Medical (ISM) bands and were originally put in place by the FCC to allow developers to experiment with various RF communication schemes without being burdened by the licensing process. Today the ISM bands are dominated by commercial products (e.g. cordless telephones and wireless data networks).

SUMMARY

In this paper we have reviewed the basics of digital modulation and attempted to show why these modulation schemes are important to wireless data transmission. Spread spectrum was also reviewed showing how its deployment can further enhance a wireless system's performance. The next article in the series will cover some of the more popular applications of this technology (e.g. 802.11, Bluetooth).

References

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