Selecting Mixed-Signal Components for Digital Communication Systems–II

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Part I, in Analog Dialogue 30-3, provided an introduction to channel capacity and its dependence on bandwidth and SNR. This installment discusses a variety of modulation schemes, and the demands each places on signal processing components.

Digital Modulation Schemes: The first installment in this series showed how limitations of SNR and bandwidth constrain the bit capacity of a communication system that uses pulse amplitude to convey bit information. As a way to encode digital bits, pulse amplitude is one of many modulation schemes used in digital communications systems today; each has advantages and disadvantages. We define below some of the more common modulation types, highlighting their basic principles, and noting the typical component specifications that impact performance. The textbooks listed on page 12 can provide more complete descriptions of these modulation schemes.

PAM—pulse amplitude modulation: (discussed earlier) encodes the bit values in the amplitude of a stream of pulses sent down the channel. The theoretical bandwidth (in Hz) required is at least 1/2 the symbol rate; practical implementations use more bandwidth than this. PAM is typically a baseband modulation scheme: it produces a signal whose spectral content is centered on dc. The simplest case, where each symbol represents the presence or absence of a single bit, is called pulse-code modulation.

Since the bit value is encoded in the amplitude of the signal, gain and offset of the components in the signal path affect system performance. Higher-order modulation schemes using more than two levels will need correspondingly better amplitude accuracy in the system components. Offset, which can shift the signal from the proper level threshold, creating a biased tendency to misinterpret bits high (or low) in the presence of noise, should be controlled. Bandwidth of the components is also an important consideration. As shown earlier, limited bandwidth produces undesirable intersymbol interference. Filtering may be used to carefully control the bandwidth of a transmitted signal, but signal processing components should not unintentionally limit the bandwidth. Generally, components should have enough bandwidth so that the channel itself is the band-limiting factor, not the signal processing circuitry.

AM—amplitude modulation: closely related to PAM, straight AM represents transmitted data by varying the amplitude of a fixed-frequency carrier, usually a sine wave, of designated frequency, f_C. Conceptually, this can be produced by taking the basic PAM signal, band-limiting it to reduce harmonic content, and multiplying it by a carrier at a fixed frequency, f_C. The result is a double-sideband signal, centered on the carrier frequency, with bandwidth twice that of the bandlimited PAM signal.

As with the PAM case, components in the signal chain must be selected to maintain amplitude integrity within the band centered around the carrier frequency, f_C. In this case, analog components may be evaluated based on their linearity, THD (total harmonic distortion) or SFDR (spurious free dynamic range) performance at f_C. For multi-bit symbols with numerous distinct amplitude levels, noise may be an important consideration in component specification.

FM/FSK—frequency modulation/frequency shift keying: We've shown that amplitude modulation schemes (including PAM) can be very sensitive to voltage noise and distortion. Alternatively, information can be encoded in the *frequency* of the sine wave being sent, so that signal attenuation or other amplitude-based disturbance would not tend to corrupt the recovered data (FM radio's resistance to static and signal degradation compared to AM are well-known analog examples; similar principles apply for digital transmission). In a simple binary case of one-bit-per-symbol, the transmitted signal would shift between frequencies f_0 ("0") and f_1, ("1"), on either side of an average, or carrier, frequency—*frequency shift keying* (FSK). It is important to note that the transmitted signal bandwidth actually spreads over a larger bandwidth than just the span between f_0 and f_1, because the speed of transitioning between the two frequencies generates additional spectral content. To simplify receiver design, it is desirable that the symbol rate be substantially less than the difference between f_0 and f_1; this makes changes in frequency easier to detect.

Frequency modulation significantly reduces the sensitivity to amplitude errors in the signal path. Since all the useful information is held in the frequency domain, many FSK receivers feature a *limiter*, a high-gain circuit designed to convert a variable-amplitude sinusoidal signal to a more nearly constant-amplitude square wave, desensitizing the circuit to component non-linearities and making it easier for subsequent processing circuitry to detect the frequency of the signal (even by counting crossings within a given time interval). Signal bandwidth is at least as important as with AM: intersymbol interference still results from insufficient processing bandwidth. Because a carrier frequency must be processed, the required bandwidth is probably significantly larger than PAM modulation of the same data. These systems are typically more sensitive to timing errors, such as jitter, than to voltage noise.

PM/QPSK—phase modulation/quadrature phase shift keying: phase and frequency are closely related mathematically; in fact, phase is the integral of frequency (e.g., doubling frequency causes phase to accumulate at twice the original rate). In PM, the signal is encoded in the phase of a fixed-frequency carrier signal, f_c. This can be accomplished with a direct digital synthesizer (DDS) that generates a digital sine wave, whose phase is modulated by a control word. A D/A converter restores the sine wave to analog for transmission.

Another example of how a 2-bit phase-modulated symbol may be derived can be seen with two equal sinusoidal components at the same frequency: in-phase (I) and quadrature (Q), 90° apart, each representing digital "1" if non-inverted, "0" if inverted (shifted 180°). When they are added, their sum is a single wave at the same frequency with 4 unique phases, 90° apart (i.e., 45°, 135°, 225°, and 315°), corresponding to the phases of the I and Q waves. Figure 1 is a "unit-circle" or "satellite" plot, graphically representing these combinations. Systems embodying this principle of phase modulation are often referred to as quadrature phase-shift keying (QPSK). As with FM, the relationship between the bandwidth of the transmitted spectrum and the symbol rate is fairly complicated. There are several variations of phase modulation, including DQPSK (differential QPSK). These types of modulation schemes are popular in difficult environments such as cellular telephony,

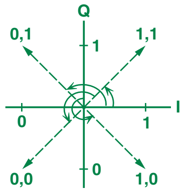

Figure 1. 2-bit QPSK phases.

because the phase information can be maintained in the presence of noise and the distortion introduced by power amplifiers.

As with FSK, components for PSK systems are typically selected based on bandwidth and other frequency domain specifications. Limiters may be used to eliminate amplitude noise. Timing errors, including jitter, effectively become "phase noise," making it more difficult to properly interpret the received signal. Modulator/demodulator units may be implemented in a quadrature arrangement, where the I and Q components are separated and processed separately through part of the signal chain. Here amplitude- and phase match between the I and Q paths are important specifications, since any mismatches map to an effective phase error.

QAM—Quadrature Amplitude Modulation: Returning to Figure 1, the representation of the four different phases of the carrier in a QPSK system, note that each of the phases also has an amplitude that is the vector sum of the I and Q amplitudes; since the amplitudes are equal, the amplitudes of the vector sums are equal. More bits per symbol could be transmitted if, instead of just two levels for I and Q, they were further quantized; then, by adding the differing amounts of sine (I axis) and cosine (Q axis) together, the combination in vector sums would modulate both amplitude and phase. Figure 2a shows the use of 2-bit quantization of both I and Q to realize 16 unique states of the carrier in each symbol, allowing transmission of 4 bits per symbol. This modulation could be produced by varying the phase and amplitude of the generated carrier directly using, for example, direct digital synthesis. More commonly, amplitude-modulated I and Q (sine and cosine) versions of the carrier are combined.

Hence the term *quadrature amplitude modulation* (QAM): the two quadrature versions of the carrier are separately amplitude modulated, then combined to form the amplitude- and phase-modulated resultant. The plot in Figure 2a, showing the various possible combinations of I and Q, is referred to as a "constellation." Note that very large constellations can, in concept, be used to represent many bits per symbol, with a required bandwidth similar to simple QPSK of the same symbol rate. The points of the constellation represent the transmitted signal and the expected value of the received signal; but noise or distortion will displace the received signal from its ideal position; it can be misinterpreted as a different constellation point if the error is large.

Figures 2a and 2b compare the 16-point constellation (2 bits I and Q) to a 64-point constellation (3 bits I and Q). At similar transmitted power levels the constellation points for the 6-bit case are twice as close together, therefore the "error threshold" is 1/2 as large and, for a given bit error rate, a 6-dB (approximately) better signal-to-noise ratio is required. The table shows typical SNR requirements for various sizes of QAM constellations to realize a 10^{-7} bit error rate. Note that binary I & Q information can be encoded [e.g., Gray code] so that points representing adjacent or nearby transmitted signal levels have similar bit patterns. In this way, misinterpreting a constellation point for one of its neighbors would corrupt only 1 or 2 bits of a multi-bit symbol.

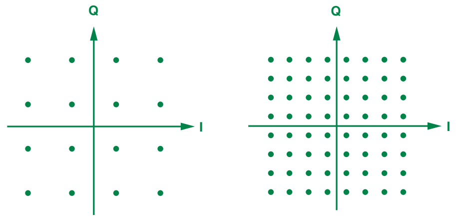

Figure 2. QAM constellations. a) 4 bits: 2-bit I and 2-bit Q. b) 6 bits: 3-bit I and 3-bit Q.

Bits/symbol (I,Q)	QAM constellation size	Required SNR
2 (1,1)	4 (QPSK)	14.5 dB
3 (1,2)	8	19.3 dB
4 (2,2)	16	21.5 dB
5 (2,3)	32	24.5 dB
6 (3,3)	64	27.7 dB
7 (3,4)	128	30.6 dB
8 (4,4)	256	33.8 dB
10 (5,5)	1024	39.8 dB
12 (6,6)	4096	45.8 dB
15 (7,8)	32768	54.8 dB

Here are some of the important specifications for components selected for QAM signal processing. *Bandwidth* should be sufficient to handle the carrier frequency, plus enough frequencies within the band to avoid introducing intersymbol interference. *Total harmonic distortion* (THD) at the carrier frequency is an important consideration, since distortion will tend to corrupt the amplitude information in the carrier. *Jitter* should be minimized to ensure that the phase information can be properly recovered. *Matching* of amplitude and phase between the I and Q processing blocks is important. Finally, *noise* (quantization and thermal) can be an important consideration, particularly for high-order constellations. Wherever practical, components should be selected to ensure that the channel itself is the noise-limiting part of the system, not the components of the signal processing system. QAM can be used to transmit many bits per symbol, but the trade-off is increased sensitivity to non-idealities in the communications channel and the signal processing components.

This provides a quick review of the basic modulation schemes. The many variations, combinations and enhancements of these approaches seek to deal with the characteristics of particular applications and the shortcomings of the various transmission techniques. They offer trade-offs between spectral efficiency, robustness, and implementation cost.

The next part of this series will explore multiplexing schemes and the variety of dynamic range requirements encountered in digital communications systems.

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