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Digital Modulation: OFDM Solves Mobility and High Rate Problems

This tutorial reviews common digital modulation methods, then provides an introduction to OFDM, an important techniques for new wireless systems

Digital modulation has evolved over time, from the first simple on-off keying (OOK) systems for primitive controls to today's high data rate WLAN and 3G wireless systems. This tutorial will briefly review the main types of digital modulation, then focus on OFDM (orthogonal frequency division multiplexing), which is a central part of new systems such as WiMax and ultra wideband (UWB).

OOK and FSK

The earliest truly digital modulation formats were on-off keying (OOK) and frequency-shift keying (FSK). OOK operates as its name suggests, with a carrier turned on and off to create a sequence of binary ones and zeros. OOK continues to be used today in extremely low cost short-range wireless links at 315 MHz, 418 MHz and 433 MHz, depending on where in the world the unit will be used. Common applications for these low data rate devices include garage door openers, automotive keyless entry and a number of consumer items such as wireless weather stations.

FSK is another simple method, alternating between two frequencies that correspond to the one and zero binary states. The advantage of FSK over OOK is that the carrier is continuous and keying is done at a very low signal level. This makes higher keying rates possible, as well as improved performance in the presence of noise. Many years ago, much of the international news transmission, military and government teletype communication was transmitted in the short wave bands using FSK or its related AFSK (audio frequency shift keying). AFSK also has a constant carrier, but uses the transition between two modulated audio frequencies to designate the binary sequence.

BPSK and QPSK

The various forms of phase shift keying (PSK) gained widespread use when computer usage required the transmission of data at higher rates. The first applications include both microwave communications links and the read/write process for magnetic tape data recording. Current disk drive technology uses refined techniques that are derived from these earlier systems.

The popularity of BPSK (binary PSK) is in its robust performance in low signal-to-noise environments. BPSK uses phase inversion (0 and 180 degree phase shift) as the two binary states. Such changes are easily detected using conventional RF mixers, so BPSK provided a significant performance improvement using conventional RF circuitry. The simplicity of BPSK was exploited to make extremely low cost paging receivers when that application became popular. Many of those receivers used a direct conversion architecture, the earliest large-scale application of that technique.

Another popular member of the PSK family is QPSK (quaternary PSK). This modulation method uses 90-degree increments in phase, resulting in four possible logic states at any instant. This increases the data rate transmission within the same bandwidth as BPSK, but with additional complexity in its generation and detection.

The easiest system architecture for QPSK is actually two BPSK modulators or demodulators. A single local oscillator is common to both, but with a phase shift of 90 degrees between the inputs to each BPSK unit.

Similarly, 8PSK systems can be obtained, with eight possible states, using 45 degrees as the incremental phase difference.

There are many variations that affect the overall performance of these systems. For example, differential PSK (DPSK or DQPSK) has a reference that is absolute phase, e.g. zero degrees. Thus, a change from one state to another contains more information—a change from +45 to +135 degrees is not just a relative +90 degree change, it is a change from one specific state to another.

To do this requires synchronization between the transmitter reference frequency and the receiver's local oscillator chain. Without going into detail, this can be accomplished by sending a "training sequence" with known parameters, by phase locking the receiver to the average phase of the transmitter (requiring coding that has a net phase variation that is constant), or by locking to an external high stability source, which today is typically GPS, but in the past may have been a cesium or rubidium oscillator, a more expensive solution!

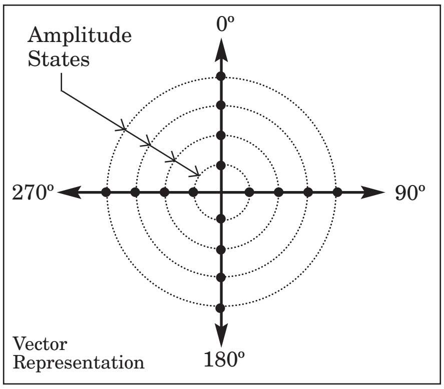

Figure 1 · 16QAM with four phase states and four amplitude states.

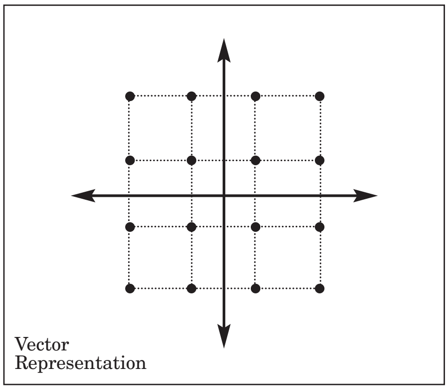

Figure 2 · Typical 16QAM with equal separation between states.

Various QAM Types

Higher data rate can be achieved in a single channel by using amplitude levels as well as phase states, as in quadrature amplitude modulation (QAM). For example, a system with 4 phase states and 4 amplitude states has a total of 16 possible data states (16QAM) at any instant (Figure 1). The vector plot of Figure 1 shows that the low-amplitude states are much closer together than the high-amplitude states. Thus, the signal-to-noise ratio of the inner states is lower than the outer ones. To correct this condition, phases other than 0/90/180/270 and different amplitude levels are selected to create a rectangular pattern when viewed in polar coordinates, as in Figure 2. This results in the maximum signal-to-noise performance, since it represents how a QAM receiver and demodulator actually behave.

As you may have observed, QAM is a linear system, while PSK is not. PSK modulations are popular in the variable environment of terrestrial mobile communications, while QAM is better suited for maximizing the data rate in well-controlled systems such as point-to-point microwave links and satellite links.

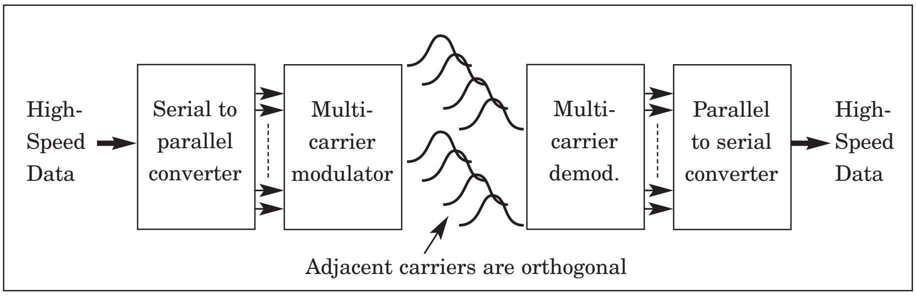

Figure 3 · OFDM allows high-speed data to be sent via multiple lower-speed channels, minimizing multipath effects in mobile environments.

OFDM—Today's Solution for High Data Rate and Mobility

Briefly, orthogonal frequency division multiplexing (OFDM) is the use of one of the above modulation types on each of several carriers. Adjacent channel carriers are shifted by 90 degrees relative phase (orthogonal) to minimize interaction. Initially used for multiple independent signals, OFDM is seeing extensive use in robust high data rate applications, particularly for mobile data such as 802.11g WLAN and 802.16e WiMAX. OFDM is also used for ultra wideband (UWB), digital audio broadcasting (DAB) and the European digital television standard (DVB-T).

OFDM is needed to combat the effects of multipath, which limits the available data rate based on speed of the mobile user and the frequency. At 5 GHz, multipath effects have increased to the point where high date rate mobile systems are virtually impossible to implement.

OFDM solves the problem by allowing a high-speed data stream to be divided into multiple channels, each of which has a low enough data rate to be transmitted reliably at the operating frequency (Figure 3). When decoded at the receiver, the high-speed data stream is reconstructed to deliver the data to the user at the full input rate.

Fortunately, modern OFDM does not require a separate transmitter and receiver for each carrier. Discrete Fourier transform (DFT) techniques and appropriate coding allow all the "hard work" of the modulator and demodulator to be accomplished using digital signal processing.

This mathematical complexity requires significant research and development effort, but with DSP implementation, once the parameters are established that optimize performance for a specific application, OFDM equipment is easily replicated for large-scale production.