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Fundamentals of OFDM: Orthogonal Frequency Division Multiplexing

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Here is basic information on OFDM, which is used to support high data rates in both wireless and wireline communication systems

Various modulation formats are used to address the performance requirements of each type of wireless transmission. Some emphasize circuit simplicity, while others support maximum data rate, robust interference rejection, or are tailored for the specific information being transmitted.

One modulation scheme of recent interest is Orthogonal Frequency Division Multiplexing (OFDM). This modulation is one of several that can support high data rates. Its advantage is an ability to handle time-varying propagation, e.g., the mobile environment.

At frequencies of 1 GHz and up, the motion of a mobile user becomes very fast in terms of wavelengths per unit time. This results in a rate of change in direct and multipath signals that can be greater than the modulation rate. Both amplitude (fading) and frequency (Dopper) are affected. For reliable transmission, the data rate must be slow enough to be detected in the presence of these variations. This allowable data rate may not be sufficient for the desired application.

Frequency Division Multiplexing (FDM) is one answer, where the transmitted signal is a composite of several modulated signals with slightly different center frequencies (see Figure 1). One high-speed data stream is divided into multiple low-speed streams, each of which is transmitted in its own channel. The data rate of each channel is low enough to survive transmission at the desired frequency and motion speed. The receiver demodulates each channel and recombines the data to achieve the original high data rate.

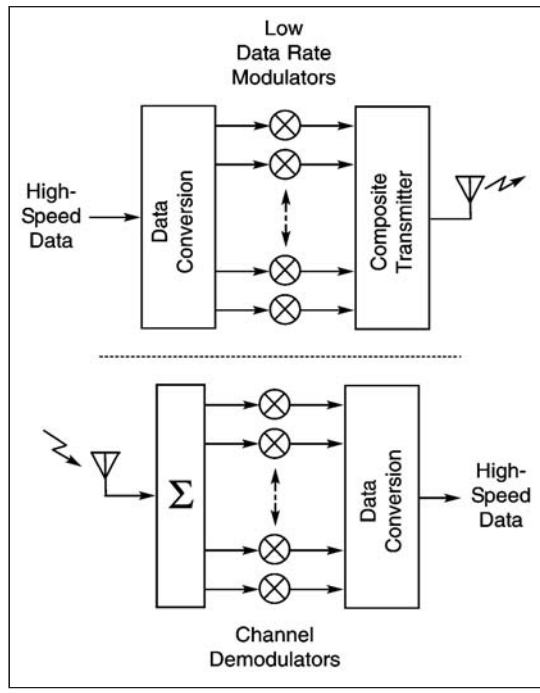

Figure 1 · A basic FDM system (transmitter at top, receiver at bottom). OFDM has the same block diagram, but uses different signal processing.

FDM has been used for many, many years in wireline and microwave communications. Rather than a single high-speed data stream, however, it has most often been used to carry many independent low-data-rate signals—telephone voice communications.

FDM is also used in Digital Subscriber Line (DSL) service, with the high-speed to multiple low-speed data rate conversion implemented for a different reason. Because DSL operates in the <50 MHz region, the use of multiple channels avoids the need for exceptionally wide percentage bandwidth modulation. It also allows selection of channel frequencies that minimize interference with commonly-used radio services that may be used in proximity to DSL lines.

FDM requires separation of the channels. In radio-based FDM, there must be a space, or *guard band* between channels to avoid interference from adjacent channels. These empty spaces are not efficient use of the spectrum. Also, when channels are placed as close together as possible, the required narrowband channel filters increase the complexity of the hardware.

The "O" in OFDM

The term *orthogonal* means "at right angles" in Euclidean three-dimensional space. For example, with orthogonal vectors, the projection of one onto the other is a single point, e.g., the dot product is zero. The term has additional meanings in mathematics, some very complex, but all refer to an independence of one function from another. The word has even made its way into common language, where an "orthogonal conversation" has two points of view with no commonality (in the past, the statement would be, "We're not talking about the same thing").

In OFDM modulation, adjacent channels are mathematically orthogonal, having a 90-degree phase shift. Like orthogonal vectors, adjacent channel signals have minimal effect on one another. This allows closer spacing between channels, and even allows some overlap of modulation sidebands. This property greatly reduces spectrum occupancy, while simplifying channel filtering. Modern digital signal processing (DSP) supports the mathematical precision required to make OFDM work effectively.

Most ADSL (Asymmetric DSL) systems now use OFDM to pack channels closer together. The objective here is higher data rate rather than reduced spectrum occupancy, but the principle of "more bits per MHz" is the same as with transmitted OFDM.

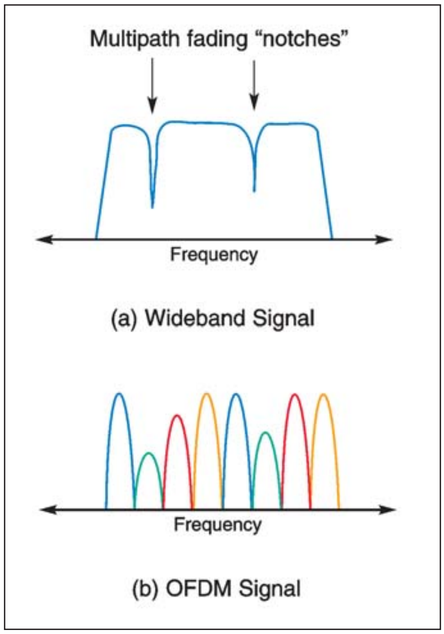

Figure 2 · A wideband signal (a) and OFDM (b) in the presence of fading. A wideband signal can be completey disrupted, while OFDM has the advantage of data loss only in a small number of channels, which can be restored by proper coding and error detection.

OFDM in the Real World

The above description might seem too good to be true—we just split up the data and send it in many channels because it won't work as one big wideband channel. While OFDM is a valuable solution to microwave transmission in a mobile environment, there are limitations.

OFDM is not immune to the multipath fading of a mobile communicatons channel, but it reduces the effects. Figure 2 illustrates how multipath fading "notches" (single-frequency cancellations) only affects individual channels of the OFDM signal. The small loss of data can be restored by error detection and coding schemes such as packetized data. In a mobile environment, the notches are dynamic, varing in depth and frequency as the propagation changes.

Another challenge of OFDM is the need for a highly linear transmitter. The multi-tone nature of the OFDM composite signal will generate a large number of intermodulation distortion products, which must be kept to a very low level. Failure to achieve the necessary linearity will reduce system reliability by creating interference between channels.

Referring to Figure 1, it might seem that OFDM's complexity is overwhelming for some applications. However, modern DSP allows the channel modulation and demodulation to be performed digitally. While this is certainly a challenge to DSP code authors, and requires substantial processing power, it is much less complex than a fully analog implementation with a separate receiver for each channel.

The final concern with OFDM is the relative lack of user experience. IEEE 802.11 systems have used OFDM since about 2000, with more recent applications in DRM (Digital Radio Mondial) and DVB-T (digital television used in most areas outside the U.S.). Mobile OFDM in WiMAX and some proposed 4G systems may expose unexpected shortcomings, although testing and simulation have likely resolved the major issues.

Numerous OFDM Applications

In addition to those already mentioned, OFDM applications include Eureka 147 Digital Audio Broadcasting, powerline communications and wireless system backhaul, with others in development. As operating frequencies continue to increase, and as mobile applications grow, OFDM will often be the best choice for transmission.

For information beyond the basic tutorial level, readers are directed to textbooks, technical papers and other educational resources.