White Paper

Wideband Orthogonal Frequency Division Multiplexing (W-OFDM)

Orthogonal Frequency Division Multiplexing (OFDM) has been successfully applied to a wide variety of digital communications applications over the past several years and has been adopted as the wireless LAN standard. This paper presents the challenges associated with implementing OFDM for high speed wireless data communication and how Wide-band OFDM (W-OFDM), a variation of OFDM improves bandwidth and noise tolerance.

Introduction

Just what is OFDM, and what makes it better? To answer this question, we need to review some basic ideas about wireless telecommunications systems, and how OFDM fits into the overall picture.

In what follows, we will review the following concepts needed to understand OFDM; digital messages, carrier waves, modulation and multiplexing. Then we will explain OFDM and why it is used.

Messages

Wireless communications systems are used to send messages between two locations using radio waves which travel across free space. Messages of all types (voice, music, image, video, text) are usually converted to digital form and are represented as a stream of 1's and 0's called bits (binary digits). Voice messages can be represented by about 10,000 bits per second, CD quality music needs about 100,000 bits/sec, and TV quality video messages require about 1,000,000 bits per second, plus or minus. Text messages can be sent at any speed, depending on how long you are willing to wait.

Carrier Waves

Radio waves are electromagnetic waves used to carry a message over a distance. Thus radio waves are also called a carrier waves. A carrier wave looks like a sine wave, and moves like a train at the speed of light. The frequency of the carrier wave is the number of times per second that the wave train goes up and down and back up as it moves past you, and is measured in units of cycles per second or Hertz.

Carrier (electromagnetic) waves of different frequencies and wavelengths have different properties. For example, radio waves can travel through walls, but light waves cannot. Lower frequency waves tend to travel further, and can bend around corners. Higher frequency waves travel more or less only via line of sight. Thus certain parts of the radio spectrum are better suited for certain types of telecommunications. For indoor wireless communications through walls over a distance of several hundred feet, or outdoor communications over several miles mostly over line of sight with perhaps some trees in the way, carrier frequencies in the range of 1 to 5 GHz (gigahertz or billion cycles per second) are used.

Modulation

Modulation is the process whereby a carrier wave of a particular frequency is modified or modulated by the message signal, so that the modulated carrier wave can be used to carry the message over a distance. For digital messages (a stream of 1's and 0's), there are three basic kinds of modulation:

- Amplitude Shift Keying (ASK) (digital AM) in which the amplitude of the carrier wave is modulated in step with the message signal.
- Frequency Shift Keying (FSK) (digital FM) in which the frequency of the carrier wave is modulated in step with the message signal.
- Phase Shift Keying (PSK) (digital PM) in which the phase of the carrier wave is modulated in step with the message signal.

ASK and PSK may also be used at the same time on one carrier, which is called Quadrature Amplitude Modulation (QAM) or Amplitude/Phase Keying (APK). The receiver is designed to receive the carrier wave, detect these amplitude and phase shifts in the carrier (demodulation), and thus retrieve the digital message.

When a carrier wave is modulated, it is no longer a single frequency but is spread out over a range of frequencies. The bandwidth of the modulated carrier wave is the range from lowest to highest frequency, with the original carrier frequency in the center. The bandwidth is approximately equal to the speed of the digital message, e.g. 10,000 Hz (10 KHz) for voice or 1,000,000 Hz (1 MHz) for video.

OFDM (Orthogonal Frequency Division Multiplexing) is a method of using many carrier waves instead of only one, and using each carrier wave for only part of the message. OFDM is also called multicarrier modulation (MCM) or Discrete Multi-Tone (DMT). We first describe Multiplexing, then Frequency Division and then Orthogonal. It is important to stress that OFDM is not really a modulation scheme since it does not conflict with other modulation schemes. It is more a coding scheme or a transport scheme.

Multiplexing

Multiplexing is a way to split a high speed digital message into many lower speed ones. A useful analogy is a highway with a toll collection point. Where each car is one bit of the message, and the number of cars passing a given point in one second is the speed of the message, which represents bits per second. The single lane highway may be split into 10 different lanes for paying tolls. At a point beside the single lane highway, the cars will pass at high speed, whereas at the toll booths, the cars will pass slowly. Thus the single high speed message (flow of cars past a point of single lane highway) is divided into many low speed messages (flow of cars past many toll booths). In a perfect system, the first car will take the first toll lane, the second car takes the second toll lane, etc. The 11th car takes the first toll lane again, and follows the first car. A multiplexer is a switch that assigns each car to one of the many toll booths.

Demultiplexing is the opposite, where many low speed messages are combined into one high speed message. Following the analogy, demultiplexing is where the many low speed messages (cars) passing slowly through the toll booth lanes are merged back into a high speed message traveling quickly on a single lane highway.

Frequency Division

Frequency division is where each toll booth lane represents a different carrier frequency or simply the carrier. Orthogonal is a mathematical term used to describe axese and functions that do not influence each other.

Orthogonal Frequency Division

Orthogonal Frequency Division is where the spacing between carriers is equal to the speed (bit rate) of the message (explained in more detail later).

In earlier multiplexing literature, a multiplexer was primarily used to allow many users to share a communications medium like a phone trunk between two telephone central offices. In OFDM, it is typical to assign all carriers to a single user; hence multiplexing is not used with its generic meaning.

Orthogonal frequency division multiplexing is then the concept of typically establishing a communications link using a multitude of carriers each carrying an amount of information identical to the separation between the carriers.

In comparing OFDM and single carrier communication systems (SCCM), the total speed in bits per second is the same for both, 1 Mbit/sec (Mbps) in this example. For single carrier systems, there is one carrier frequency, and the 1 Mbps message is modulated on this carrier, resulting in a 1 MHz bandwidth spread on both sides of the carrier. For OFDM, the 1,000,000 bps message is split into 10 separate messages of 100,000 bit/sec each, with a 100 KHz bandwidth spread on both sides of the carrier.

To illustrate how frequencies change with time, we can use the analogy of the sounds of an orchestra or band. One carrier wave is analogous to one instrument playing one note, whereas many carriers is analogous to many instruments playing at once. Single carrier systems using a high speed message is analogous to a drum roll where the sticks are moving fast. Multicarrier systems (OFDM) using many low speed messages is analogous to many instruments playing more slowly.

A final comparison between OFDM and SCCM is to state that SCCM carry the information is a serial manner whereas OFDM carries the information in a parallel manner.

A more detailed understanding of Orthogonal arises when we observe thatthe bandwidth of a modulated carrier has a so called sinc shape (sinx/x) with nulls spaced by the bit rate. In OFDM, the carriers are spaced at the bit rate, so that the carriers fit in the nulls of the other carriers. Another view of Orthogonal is that each carrier has an integer number of sine wave cycles in one bit period.

How to Implement OFDM?

Original multicarrier systems were implemented through the generation of a number of carriers using separate local oscillators. This was inefficient and costly (though increased the data rate). When a mathematical transform (the fast Fourier transform - FFT) was introduced to generate the different individual carriers and ensure their orthogonality, OFDM was reborn. The FFT basically calculates the spectral content of the signal. It moves a signal from the time domain where it is expressed as a series of time events to the frequency domain where it is expressed as the amplitude and phase of a particular frequency. The inverse FFT (IFFT) performs the reciprocal operation.

Data (which can be digitized speech, digitized video or computer data) is coded for security or error correction. It is then modulated by some form of QAM (QAM, 16QAM or 64QAM for example). In single carrier systems, the data would then be placed at the appropriate frequency for transmission. In OFDM, the data is then framed into frames of a suitable size for an FFT. An FFT should be of length 2^r (where r is an integer). Not all 2^r points in the FFT are used to carry the information; some points are placed for fine-tuning the frequency or for tracking the timing of the bits. An IFFT is performed on the frames. Each frame output from the IFFT is placed at the appropriate frequency for transmission.

In the receiver, the inverse operations are performed and data is recovered. However, as the FFT is performed in the receiver, the data is then in the frequency domain which makes correcting the imperfections of the channel simple.

OFDM was known since the mid 50s. Why W-OFDM is only becoming popular in 2000 is because economical integrated circuits that can perform a high speed FFT real time were not available until 1998.

Peak-to-Average Ratio (PAR) Problem

A characteristic of FFT is that if the input to it happened to be a sinusoid, the output will be a pulse of height 2^r. If the input was a pulse of some height, the output would be a sinusoid of height 1. This means that the output of the FFT has a minimum dynamic range of $10\log2^r$. Dynamic range is a term used to define the linearity requirement of a system. It represents the ability of the system to honestly reproduce the signals input into it. The dynamic range of an OFDM system then is typically larger by as much as two to four times that of a single carrier system. The dynamic range increase leads to an increase in the cost both in terms of dollars and power consumption of the transmitter amplifier. This PAR problem is one of the reasons early high speed OFDM systems were only implemented in broadcasting applications.

Why Use OFDM?

When the radio signals travel from one location to another, they may bounce off surrounding objects (Figure 1), resulting in multiple paths between transmitter and receiver. This is analogous to echoes or reflections causing multiple copies of the message to arrive at the receiver at different times. The combination of all paths at the receiver causes the modulated message signal to be distorted.

A simple example is where there are only two paths, the line of sight path and a reflected path from the ground. If a message is sent at the right speed, then the second (reflected) copy of the message may arrive exactly one bit time later than the first (direct) copy. The receiver will then receive two different bits mixed together, thus distorting the original message bit (Figure 1). Wireless communication systems have to be designed to cope with this so-called multipath distortion.

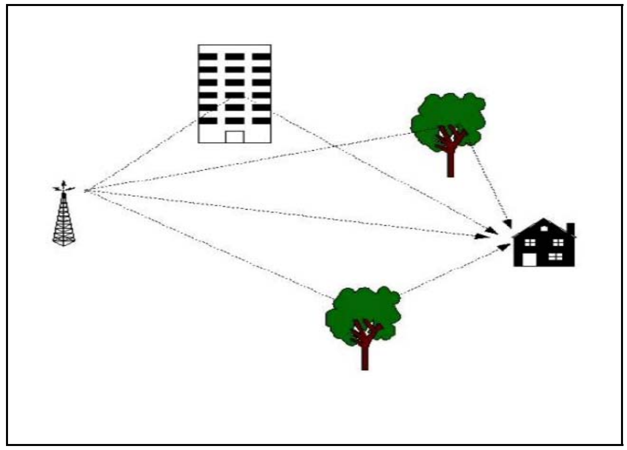

Figure 1. Multi-Path Distortion

The main idea of using OFDM is to avoid problems caused by multipath reflections by sending the message bits slowly enough so that any delayed copies (reflections) are late by only a small fraction of a bit time. To maintain a high bit rate, multiple carriers are used to send many low speed messages at the same time which can be combined at the receiver to make up one high speed message. In this way, we avoid the distortion caused by reflections. If SCCM is used instead of OFDM, then the delayed copies of bits will be mixed together by the multipath, and the multipath distortion must be cancelled out using a so-called equalizer. Such equalized systems can work well, but they are subject to problems caused by imperfect cancellation of the multipath. If the delay spread (the period of time where replicas of a bit are still arriving at the receiver) is n bits long, conventional equalizers need n^2 (order of magnitude) operations to remove the effects of multipath.

Typically, the maximum data rate, without equalization, is between 20kbps and 1Mbps depending on the environment. W-OFDM systems are designed such that broadband communications are achievable whereas the data rate for each individual carrier is below this rate. Hence, an equalizer is not needed. However, to achieve a high data rate, a wide frequency band must be used. This leads to that different carriers may be subjected to propagation channels of different characteristics (different attenuation or phase distortion). W-OFDM removes these effects by calculating the attenuation and phase distortion of the propagation channel (the channel's frequency response). This is done by transmitting a frame with no information in it. The FFT received frame is then the frequency response of the channel. Multipath distortion is removed by dividing each frame of bits by this channel frequency response. The cost of this saving is performing an FFT which has an $n\log_2 n$ operations order of magnitude.

Recent advances in very-large-scale integration (VLSI) technology make high speed, large-size FFT chips more affordable. Moore's law suggests that we will continue to see improvements in the available speeds of VLSI which would increase the speed of OFDM systems and single carrier systems (with equalizers). Figure 2 compares the speeds possible with an OFDM system to those possible with a single carrier systems (with equalizers).

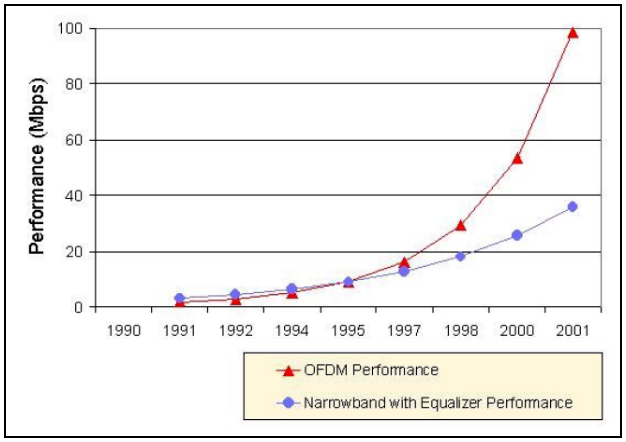

Figure 2. Comparison of the speeds possible with OFDM systems and single carrier systems.

Wideband OFDM

Wideband OFDM (W-OFDM) is a variant of OFDM where the spacing between carriers is chosen to be large enough, so that any frequency errors between transmitter and receiver are only a small fraction of the spacing, and thus have a negligible effect on the performance of the system. W-OFDM is the only way broadband communications can be established with OFDM.

W-OFDM was invented by Wi-LAN and it observes that in OFDM an error in the timing of the digitization bits (of the analog signal received from the radio) will become phase offsets after the FFT that can be removed through the division by the channel's frequency response. Also, an offset in the frequency locally generated in the receiver from that transmitted will translate into a sampling error that can be tolerated.

In April 2006, EION Wireless acquired several major product lines from Calgary based Wi-LAN Inc. Many of these products use Wi-LAN's patented W-OFDM technology.

Wi-LAN introduced a randomizing phase into the data before it was presented to the FFT. This randomizing, though originally an encryption mechanism, destroyed any sinusoid or pulse relationships in the input to the FFT. This reduced the dynamic range required of the transmitter amplifiers and opened the door for low cost systems.

The advantages to W-OFDM where OFDM had some drawbacks compared to single carrier communication systems are:

- Optimal performance against Multipath
- Less sensitive to carrier offset
- Optimal power efficiency of the transmitter amplifier
- The average value of the slope of the phase of the frequency response is indicative of the group delay (which in turn is a measure of the separation between the transmitter and the receiver).
- More immune against fading (whereby the whole signal is shadowed by an obstruction) since it is unlikely that the whole frequency band will be obstructed.

Summary

In the past decade, OFDM was used for wideband data communications over mobile radio FM channels, digital audio broadcasting (DAB), digital video broadcasting — Terrestrial (DVB-T), high-bit-rate digital subscriber lines (HDSL; 1.6Mbps), asymmetric digital subscriber lines (ADSL; less than 6Mbps), very-high-speed digital subscriber lines (VDSL; 100Mbps). W-OFDM is currently implemented in EION's Libra MAX family of products for point-to-point and point-to multipoint broadband wireless access solutions. W-OFDM is the basis for wireless LANs (IEEE802.11a and ETSI BRAN HiperLAN/2) standards.

The Internet has been the medium that facilitates interactive, multimedia applications that require increasingly greater bandwidth capacity. The next evolution of wireless will be in data communications applications that can deliver broadband services to anyone, anytime, anywhere. With the combination of high bandwidth and increase in signal integrity, W-OFDM will open up new markets for applications.

Wi-LAN's W-OFDM patents: United States patents number 5,282,222 and 5,555,268 and Canada patent number 2,064,975

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