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Orthogonal Frequency Division Multiplexing (OFDM)

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Abstract--Orthogonal frequency-division multiplexing (OFDM) is a method of encoding digital data on multiple carrier frequencies. OFDM has developed into a popular scheme for wideband digital communication, whether wireless or over copper wires, used in applications such as digital television and audio broadcasting, DSL Internet access, wireless networks, power line networks, and 4G mobile communications. OFDM is a frequency-division multiplexing (FDM) scheme used as a digital multi-carrier modulation method. A large number of closely spaced orthogonal sub-carrier signals are used to carry data on several parallel data streams or channels. The orthogonality allows high spectral efficiency, with a total symbol rate near the Nyquist rate for the equivalent baseband signal (i.e. near half the Nyquist rate for the double-side band physical passband signal). Almost the whole available frequency band can be utilized. OFDM generally has a nearly 'white' spectrum, giving it benign electromagnetic interference properties with respect to other co-channel users. The primary advantage of OFDM over single-carrier schemes is its ability to cope with severe channel conditions (for example, attenuation of high frequencies in a long copper wire, narrowband interference and frequency-selective fading due to multipath) without complex equalization filters. In OFDM, the sub-carrier frequencies are chosen so that the sub-carriers are orthogonal to each other, meaning that cross-talk between the sub-channels is eliminated and inter-carrier guard bands are not required. This greatly simplifies the design of both the transmitter and the receiver; unlike conventional FDM, a separate filter for each sub-channel is not required.

I. INTRODUCTION

Recently, a worldwide convergence has occurred for the use of Orthogonal Frequency Division Multiplexing (OFDM) as an emerging technology for high data rates. In particular, many wireless standards (Wi-Max, IEEE802.11a, LTE, DVB) have adopted the OFDM technology as a mean to increase dramatically future wireless communications. OFDM is a particular form of Multi-carrier transmission and is suited for frequency selective channels and high data rates. This technique transforms a frequency-selective wide-band channel into a group of non-selective narrowband channels, which makes it robust against large delay spreads by preserving orthogonality in the frequency domain. Moreover, the ingenious introduction of cyclic redundancy at the transmitter reduces the complexity to only FFT processing and one tap scalar equalization at the receiver1 Orthogonal Frequency Division Multiplexing or OFDM is a modulation format that is being used for many of the latest wireless and telecommunications standards. OFDM has been adopted in the Wi-Fi arena where the standards like 802.11a, 802.11n, 802.11ac and more. It has also been chosen for the cellular telecommunications standard LTE / LTE-A, and in addition to this it has been adopted by other standards such as WiMAX and many more. Orthogonal frequency division multiplexing has also been adopted for a number of broadcast standards from DAB Digital Radio to the Digital Video Broadcast standards, DVB. It has also been adopted for other broadcast systems as well including Digital Radio Mondi ale used for the long medium and short wave bands. Although OFDM, orthogonal frequency division multiplexing is more complicated than earlier forms of signal format, it provides some distinct advantages in terms of data transmission, especially where high data rates are needed along with relatively wide bandwidths. Orthogonal frequency-division multiplexing (OFDM) is a method of digital modulation in which a signal is split into several narrowband channels at different frequencies. The technology was first conceived in the 1960s and 1970s during research into minimizing interference among channels near each other in frequency. In some respects, OFDM is similar to conventional frequency-division multiplexing (FDM). The difference lies in the way in which the signals are modulated and demodulated. Priority is given to minimizing the interference, or crosstalk, among the channels and symbols comprising the data stream. Less importance is placed on perfecting individual channels. OFDM is used in European digital audio broadcast services. The technology lends itself to digital television, and is being considered as a method of obtaining high-speed digital data transmission over conventional telephone lines. It is also used in wireless local area networks.

II. OVERVIEW

As illustrated in Figure 1 the structure of the OFDM receiver is completely exposed to GNU Radio Companion, a graphical tool to setup and configure signal processing throw graphs. The receiver is divided into two functional parts: The first part, depicted in the top half, is responsible for frame detection. The second part, shown in the bottom half, is responsible for decoding the frame. In the following, we briefly discuss some specific GNU Radio features we used, before explaining the signal processing blocks in detail. Stream tagging: GNU Radio was initially designed for stream based signal processing. Stream tags have been introduced to annotate the sample stream with further meta data, like sampling frequency, carrier frequency, or timestamps. We employ stream tagging to signal the start of an OFDM frame, and in a later stage the length and encoding scheme of the frame. Message passing: GNU Radio is often used to implement packet based transceiver systems, e.g., IEEE 802.11 or IEEE 802.15. The implementation of such technologies is complicated in a stream-based environment, thus, message passing was introduced. Messages can, like stream tags, encapsulate arbitrary information. Thus, processing blocks can work on complete packets and switch to stream-based processing only at selected stages in the signal processing chain. Vectorized Library of Kernels (VOLK): In order to be able to support sample rates of 20Msps for IEEE802.11 a/g and 10Msps for IEEE802.11p respectively, we make use of VOLK [10], a toolkit that eases the use of Single Instruction Multiple Data (SIMD) instructions. It provides wrapper functions for the most common signal processing tasks and dynamically selects the implementation which over's the highest performance on the host system. SIMD instructions work on vectors instead of scalars, which speeds up the signal processing considerably. VOLK also takes care of all platform dependent issues of Vectorized instructions, allowing the user to write platform independent code.

A. Digital Modulation Overview

Most forms of digital transmission involve modulating a pair of summed sine waves that differ in phase by 90°. The modulation signal can be represented by the vector sum of the in-phase (I) and quadrature (Q) components, as shown in *Figure 1*. There are many ways to encode digital information in this way. If you change the phase relationships between the two sine waves, the result is called phase shift keying (PSK).

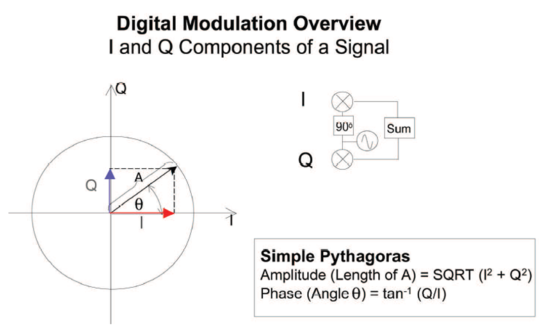

figure 1. Most forms of digital transmission involve modulating a pair of sine waves that differ in phase by 90°. The modulation signal can be represented by the vector sum of the in-phase (I) and quadrature (Q) components.

A common type of PSK is quadrature phase shift keying (QPSK), which uses four phases; if eight phases are used, the result is 8PSK. If you vary both the amplitude and phase of the two sine waves, the result is quadrature amplitude modulation (QAM). The best way to analyze the resulting signals is with a vector signal analyzer (VSA), such as the Model 2820, that processes all its data as quadrature pairs in a constellation diagram; *Figure 2* shows constellation diagrams for several types of modulations: QPSK, 8PSK, and 16QAM.

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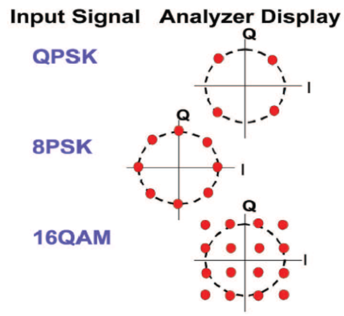

Figure 2. Constellation diagrams for several types of modulation.

B. Orthogonality

The main aspect in OFDM is maintaining orthogonality of the carriers. If the integral of the product of two signals is zero over a time period, then these two signals are said to be orthogonal to each other. Two sinusoids with frequencies that are integer multiples of a common frequency can satisfy this criterion. Therefore, orthogonality is defined by:

$$\int_0^T \cos(2\pi n f_o t)\cos(2\pi m f_o t)\,dt = 0 \quad (n \neq m)$$

Where n and m are two unequal integers; fo is the fundamental frequency; T is the period over which the integration is taken. For OFDM, T is one symbol period and fo set to 1/T for optimal effectiveness

III. THE MULTI-PATH PROBLEM

Multi-path adds another layer of complexity to our EVM measurement. *Figure 3* shows a Bluetooth signal with a symbol rate of 1M symbols per second. That means that the receiver will expect a specific symbol within a window of one microsecond. If multi-path delays the signal by more than one microsecond, the receiver will receive the symbol in the next symbol period, causing a significant symbol error. The faster the data rate, the higher the chance that multi-path will cause Inter Symbol Interference (ISI). An obvious way to reduce the error rate would be to slow down the symbol rate; each symbol would last longer and be more resistant to multipath. Unfortunately, this reduces the data rate. What's needed is a way to slow down the symbol rate without slowing the data rate — a seemingly impossible task. The answer to the puzzle is OFDM.

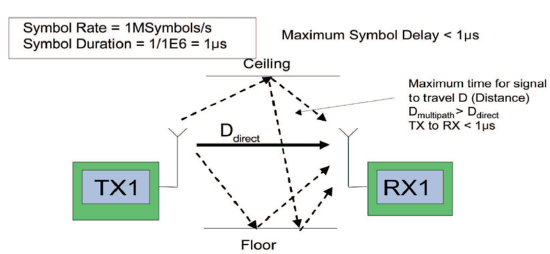

Figure 3. If the difference in path length between direct and reflected paths exceeds 1 microsecond, the receiver will receive the symbol in the next symbol period.

OFDM transmits a large number of closely-spaced carrier waves, each modulated with a different signal. *Figure 4* shows that the individual I and Q input signals are translated into separate carriers. The symbol rate for each carrier is low, making it resistant to multipath, but because there are so many carriers the overall data rate is high. Adjacent carriers are in phase quadrature with each other, which keeps crosstalk between them to a minimum without requiring a bank of narrow-band filters.

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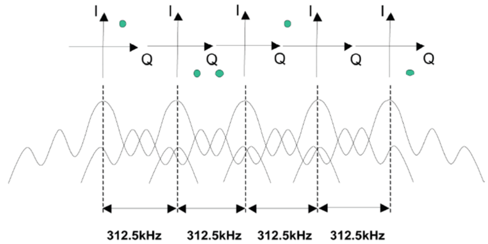

Figure 4. Instead of transmitting a single symbol at a time, OFDM transmits multiple symbols simultaneously on a number of carriers. This is the Frequency Division Multiplex component. The sub-carriers are distributed in carefully chosen multiples of frequency so that they are "orthogonal" and the closely adjacent sub-carriers don't interfere with each other.

IV. THE OFDM RADIO

As you can see, a lot of complex math is involved in this. Many conventional instruments lack the signal processing capability to perform these measurements quickly. As shown in *Figure 5*, Keithley's DSP enhanced architecture makes it possible to perform the analysis very quickly. OFDM is simple in concept, even though its implementation is complex.

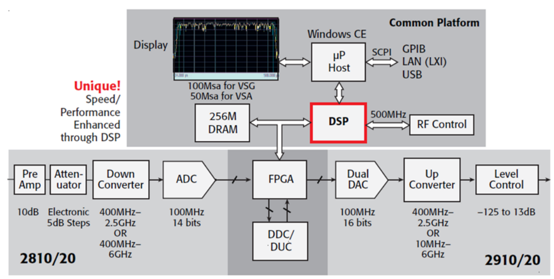

Figure 5. This block diagram shows the digital circuit in the Model 2810 Vector Signal Analyzer and the Model 2910 Vector Signal Generator.

Mathematically, it can be implemented by using an Inverse Fast Fourier Transform (IFFT) in the transmitter and conversely an FFT in the receiver. *Figure 6* shows the parallel symbols being converted to the two modulated sine waves in the output. It's as if the IFFT acts as a specialized multiplexer.

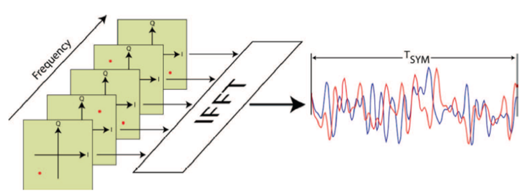

Figure 6. OFDM can be implemented by using an Inverse Fast Fourier Transform (IFFT) in the transmitter and conversely an FFT in the receiver. In the transmitter, the IFFT converts the parallel input signals into the two modulated sine waves in the output. It's as if the IFFT acts as a specialized multiplexer.

V. WLAN

WLAN is defined by the IEEE 802.11 standard, of which there are several variations, a through g, as shown in *Table 1*. Within a 16.25MHz bandwidth are 52 carriers (*Figure 7*), numbered –26 to +26, spaced 312.5kHz apart. Carriers 7 and 21 (–21, –7, +7 and +21) are the pilots. The packet structure is Preamble – Header – Data Block, and the sub-carrier modulation types are BPSK, QPSK, 16-QAM, or 64-QAM.

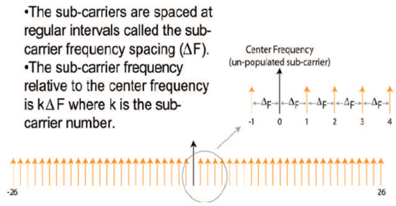

Figure 7. Each carrier within the modulation scheme is referred to as a sub-carrier. The sub-carriers are spaced at regular intervals called the sub-carrier frequency spacing (□F). The sub-carrier frequency relative to the center frequency is k□F where k is the sub-carrier number.

Table 1: WLAN Summary

802.11	Means
a	54Mbps OFDM, 5.9GHz Band, 20MHz channels
b	11Mbps CCK, 2.4GHz (Legacy, not OFDM)
g	What you can easily buy now – same as a, but at 2.4GHz
j	Japanese version of g that uses half the sample rate
n	• Not a finished standard yet • Like g, but up to 600 Mbps • OFDM • MIMO • 20 and 40MHz channels

The original WLAN standard is 802.11b, which is not based on OFDM. a and g are the same: a works in the 5GHz ISM band and g works in the 2.4GHz ISM band. j is a slower symbol rate version of g for the Japanese market, and n is based on MIMO technology, which is covered in another white paper. Several organizations are involved with WLAN: WiFi is an industry consortium that defines a required subset of 802.11 to ensure better operation between different vendors' equipment, while EWC is an industry consortium that took the unfinished n standard, agreed upon a version, and is attempting to field solutions prior to 802.11N ratification.

VI. OFDM APPLICATIONS

OFDM technique is the most prominent technique of this era .Some of its applications is given below.
DAB: DAB - OFDM forms the basis for the Digital Audio Broadcasting (DAB) standard in the
European market. Digital Audio Broadcasting (DAB) using OFDM has been standardized in Europe and is the next step in evolution beyond FM radio broadcasting providing interference free transmission.
HDTV
Wireless LAN Networks
5.3.1 HIPERLAN/2
IEEE 802.11g
IEEE 802.16 Broadband Wireless Access System.
Wireless ATM transmission system
IEEE 802.11a

VII. CONCLUSION

In terms of speed versus mobility, the WLAN and WiMAX standards provide a marked increase in data speed over traditional cellular based communications technology. The future of wireless and of fourth generation cellular systems, such as LTE or UWB, will be based on a combination of OFDM types of modulation and MIMO radio configurations. When choosing test equipment for testing today's radio standards, it's important to consider the evolution of wireless technology and to ensure that your purchases are forward compatible.

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