WiMAX

WiMAX (Worldwide Interoperability for Microwave Access) is a telecommunications protocol that provides fixed and fully mobile Internet access. The current WiMAX revision provides up to 40 Mbit/s with the IEEE 802.16m update expected to offer up to 1 Gbit/s fixed speeds. The name "WiMAX" was created by the WiMAX Forum, which was formed in June 2001 to promote conformity and interoperability of the standard. The forum describes WiMAX as "a standards-based technology enabling the delivery of last mile wireless broadband access as an alternative to cable and DSL".

Terminology

WiMAX refers to interoperable implementations of the IEEE 802.16 wireless-networks standard (ratified by the WiMAX Forum), in similarity with Wi-Fi, which refers to interoperable implementations of the IEEE 802.11 Wireless LAN standard (ratified by the Wi-Fi Alliance). The WiMAX Forum certification allows vendors to sell their equipment as WiMAX (Fixed or Mobile) certified, thus ensuring a level of interoperability with other certified products, as long as they fit the same profile.

The IEEE 802.16 standard forms the basis of 'WiMAX' and is sometimes referred to colloquially as "WiMAX", "Fixed WiMAX", "Mobile WiMAX", "802.16d" and "802.16e". Clarification of the formal names are as follow:

- **802.16-2004** is also known as 802.16d, which refers to the working party that has developed that standard. It is sometimes referred to as "Fixed WiMAX," since it has no support for mobility.
- **802.16e-2005**, often abbreviated to 802.16e, is an amendment to 802.16-2004. It introduced support for mobility, among other things and is therefore also known as "Mobile WiMAX".

Mobile WiMAX is the WiMAX incarnation that has the most commercial interest to date and is being actively deployed in many countries. Mobile WiMAX is also the basis of future revisions of WiMAX. As such, references to and comparisons with "WiMAX" in this Wikipedia article mean "Mobile WiMAX".

Uses

The bandwidth and range of WiMAX make it suitable for the following potential applications:

- Providing portable mobile broadband connectivity across cities and countries through a variety of devices.
- Providing a wireless alternative to cable and DSL for "last mile" broadband access.
- Providing data, telecommunications (VoIP) and IPTV services (triple play).
- Providing a source of Internet connectivity as part of a business continuity plan.
**Broadband**

Companies are deploying WiMAX to provide mobile broadband or at-home broadband connectivity across whole cities or countries. In many cases this has resulted in competition in markets which typically only had access to broadband through an existing incumbent DSL (or similar) operator.

Additionally, given the relatively low cost to deploy a WiMAX network (in comparison to GSM, DSL or Fiber-Optic), it is now possible to provide broadband in places where it may have not been economically viable.

**Backhaul**

WiMAX is a possible replacement candidate for cellular phone technologies such as GSM and CDMA, or can be used as an overlay to increase capacity. Fixed WiMAX is also considered as a wireless backhaul technology for 2G, 3G, and 4G networks in both developed and developing nations. \[6\] \[7\]

In North America, backhaul for urban cellular operations is typically provided via one or more copper wire line T1 connections, whereas remote cellular operations are sometimes backhauled via satellite. In most other regions, urban and rural backhaul is usually provided by microwave links. (The exception to this is where the network is operated by an incumbent with ready access to the copper network, in which case T1 lines may be used.) WiMAX is a broadband platform and as such has much more substantial backhaul bandwidth requirements than legacy cellular applications. Therefore, traditional copper wire line backhaul solutions are not appropriate. Consequently the use of wireless microwave backhaul is on the rise in North America and existing microwave backhaul links in all regions are being upgraded. \[8\] Capacities of between 34 Mbit/s and 1 Gbit/s are routinely being deployed with latencies in the order of 1 ms. In many cases, operators are aggregating sites using wireless technology and then presenting traffic on to fiber networks where convenient.

**Triple-play**

WiMAX supports the technologies that make triple-play service offerings possible (such as Quality of Service and Multicasting).

As a result, it is possible for a WiMAX operator to not only provide high-speed broadband Internet access, but also VoIP and IPTV services to customers with relative ease. This enables a WiMAX service to be a replacement for DSL, Cable and Telephony services.

On May 7, 2008 in the United States, Sprint Nextel, Google, Intel, Comcast, Bright House, and Time Warner announced a pooling of an average of 120 MHz of spectrum and merged with Clearwire to form a company which will take the name "Clear". The new company hopes to benefit from combined services offerings and network resources as a springboard past its competitors. The cable companies will provide media services to other partners while gaining access to the wireless network as a Mobile virtual network operator to provide triple-play services.

Some analysts have questioned how the deal will work out: Although fixed-mobile convergence has been a recognized factor in the industry, prior attempts to form partnerships among wireless and cable companies have generally failed to lead to significant benefits to the participants. Other analysts point out that as wireless progresses to higher bandwidth, it inevitably competes more directly with cable and DSL, inspiring competitors into collaboration. Also, as wireless broadband networks grow denser and usage habits shift, the need for increased backhaul and media service will accelerate, therefore the opportunity to leverage cable assets is expected to increase.
Rapid deployment

- WiMAX access was used to assist with communications in Aceh, Indonesia, after the tsunami in December 2004. All communication infrastructure in the area, other than amateur radio, was destroyed, making the survivors unable to communicate with people outside the disaster area and vice versa. WiMAX provided broadband access that helped regenerate communication to and from Aceh.
- WiMAX hardware was donated by Intel Corporation to assist the Federal Communications Commission (FCC) and FEMA in their communications efforts in the areas affected by Hurricane Katrina.\(^9\) In practice, volunteers used mainly self-healing mesh, Voice over Internet Protocol (VoIP), and a satellite uplink combined with Wi-Fi on the local link.\(^{10}\)

Connecting to WiMAX

There are numerous devices on the market that provide connectivity to a WiMAX network. These are known as the "subscriber unit" (SU).

There is an increasing focus on portable units. This includes handsets (similar to cellular smartphones); PC peripherals (PC Cards or USB dongles); and embedded devices in laptops, which are now available for Wi-Fi services. In addition, there is much emphasis by operators on consumer electronics devices such as Gaming consoles, MP3 players and similar devices. It is notable that WiMAX is more similar to Wi-Fi than to 3G cellular technologies.

The WiMAX Forum website provides a list of certified devices. However, this is not a complete list of devices available as certified modules are embedded into laptops, MIDs (Mobile Internet devices), and other private labeled devices.

WiMAX Gateways

WiMAX gateway devices are available as both indoor and outdoor versions from several manufacturers. Many of the WiMAX gateways that are offered by manufactures such as ZyXEL, Motorola, and Greenpacket\(^{11}\) are stand-alone self-install indoor units. Such devices typically sit near the customer's window with the best WiMAX signal, and provide:

- An integrated Wi-Fi access point to provide the WiMAX Internet connectivity to multiple devices throughout the home or business.
- Ethernet ports should you wish to connect directly to your computer or DVR instead.
- One or two PSTN telephone jacks to connect your land-line phone and take advantage of VoIP.

Indoor gateways are convenient, but radio losses mean that the subscriber may need to be significantly closer to the WiMAX base station than with professionally-installed external units.

Outdoor units are roughly the size of a laptop PC, and their installation is comparable to the installation of a residential satellite dish. A higher-gain directional outdoor unit will generally result in greatly increased range and throughput but with the obvious loss of practical mobility of the unit.
**WiMAX Dongles**

There are a variety of USB dongles on the market which provide connectivity to a WiMAX network. Generally these devices are connected to a notebook or netbook whilst on the go. Dongles typically have omnidirectional antennae which are of lower-gain compared to other devices, as such these devices are best used in areas of good coverage.

**WiMAX Mobiles**

HTC announced the first WiMAX enabled mobile phone, the Max 4G, on Nov 12th 2008. The device was only available to certain markets in Russia on the Yota network.

HTC released the second WiMAX enabled mobile phone, the EVO 4G, March 23, 2010 at the CTIA conference in Las Vegas. The device made available on June 4, 2010 is capable of both EV-DO(3G) and WiMAX(4G) as well as simultaneous data & voice sessions. A number of WiMAX Mobiles are expected to hit the US market in 2010.

**Technical information**

**WiMAX and the IEEE 802.16 Standard**

The current WiMAX revision is based upon IEEE Std 802.16e-2005 approved in December 2005. It is a supplement to the IEEE Std 802.16-2004, and so the actual standard is 802.16-2004 as amended by 802.16e-2005. Thus, these specifications need to be considered together.

IEEE 802.16e-2005 improves upon IEEE 802.16-2004 by:

- Adding support for mobility (soft and hard handover between base stations). This is seen as one of the most important aspects of 802.16e-2005, and is the very basis of Mobile WiMAX.
- Scaling of the Fast Fourier transform (FFT) to the channel bandwidth in order to keep the carrier spacing constant across different channel bandwidths (typically 1.25 MHz, 5 MHz, 10 MHz or 20 MHz). Constant carrier spacing results in a higher spectrum efficiency in wide channels, and a cost reduction in narrow channels. Also known as Scalable OFDMA (SOFDMA). Other bands not multiples of 1.25 MHz are defined in the standard, but because the allowed FFT subcarrier numbers are only 128, 512, 1024 and 2048, other frequency bands will not have exactly the same carrier spacing, which might not be optimal for implementations.
- Advanced antenna diversity schemes, and hybrid automatic repeat-request (HARQ)
- Adaptive Antenna Systems (AAS) and MIMO technology
- Denser sub-channelization, thereby improving indoor penetration
- Introducing Turbo Coding and Low-Density Parity Check (LDPC)
- Introducing downlink sub-channelization, allowing administrators to trade coverage for capacity or vice versa
- Adding an extra QoS class for VoIP applications.

SOFDMA (used in 802.16e-2005) and OFDM256 (802.16d) are not compatible thus equipment will have to be replaced if an operator is to move to the later standard (e.g., Fixed WiMAX to Mobile WiMAX).
Physical layer

The original version of the standard on which WiMAX is based (IEEE 802.16) specified a physical layer operating in the 10 to 66 GHz range. 802.16a, updated in 2004 to 802.16-2004, added specifications for the 2 to 11 GHz range. 802.16-2004 was updated by 802.16e-2005 in 2005 and uses scalable orthogonal frequency-division multiple access (SOFDMA) as opposed to the fixed orthogonal frequency-division multiplexing (OFDM) version with 256 sub-carriers (of which 200 are used) in 802.16d. More advanced versions, including 802.16e, also bring multiple antenna support through MIMO (See WiMAX MIMO). This brings potential benefits in terms of coverage, self installation, power consumption, frequency re-use and bandwidth efficiency.

MAC (data link) layer

The WiMAX MAC uses a scheduling algorithm for which the subscriber station needs to compete only once for initial entry into the network. After network entry is allowed, the subscriber station is allocated an access slot by the base station. The time slot can enlarge and contract, but remains assigned to the subscriber station, which means that other subscribers cannot use it. In addition to being stable under overload and over-subscription, the scheduling algorithm can also be more bandwidth efficient. The scheduling algorithm also allows the base station to control Quality of service (QoS) parameters by balancing the time-slot assignments among the application needs of the subscriber stations.

Deployment

As a standard intended to satisfy needs of next-generation data networks (4G), WiMAX is distinguished by its dynamic burst algorithm modulation adaptive to the physical environment the RF signal travels through. Modulation is chosen to be more spectrally efficient (more bits per OFDM/SOFDMA symbol). That is, when the bursts have a high signal strength and a high carrier to noise plus interference ratio (CINR), they can be more easily decoded using digital signal processing (DSP). In contrast, operating in less favorable environments for RF communication, the system automatically steps down to a more robust mode (burst profile) which means fewer bits per OFDM/SOFDMA symbol; with the advantage that power per bit is higher and therefore simpler accurate signal processing can be performed.

Burst profiles are used inverse (algorithmically dynamic) to low signal attenuation; meaning throughput between clients and the base station is determined largely by distance. Maximum distance is achieved by the use of the most robust burst setting; that is, the profile with the largest MAC frame allocation trade-off requiring more symbols (a larger portion of the MAC frame) to be allocated in transmitting a given amount of data than if the client were closer to the base station.

The client's MAC frame and their individual burst profiles are defined as well as the specific time allocation. However, even if this is done automatically then the practical deployment should avoid high interference and multipath environments. The reason for which is obviously that too much interference causes the network function poorly and can also misrepresent the capability of the network.

The system is complex to deploy as it is necessary to track not only the signal strength and CINR (as in systems like GSM) but also how the available frequencies will be dynamically assigned (resulting in dynamic changes to the available bandwidth.) This could lead to cluttered frequencies with slow response times or lost frames.

As a result the system has to be initially designed in consensus with the base station product team to accurately project frequency use, interference, and general product functionality.
Orthogonal frequency-division multiplexing (OFDM), essentially identical to coded OFDM (COFDM) and discrete multi-tone modulation (DMT), is a frequency-division multiplexing (FDM) scheme utilized as a digital multi-carrier modulation method. A large number of closely-spaced orthogonal sub-carriers are used to carry data. The data is divided into several parallel data streams or channels, one for each sub-carrier. Each sub-carrier is modulated with a conventional modulation scheme (such as quadrature amplitude modulation or phase-shift keying) at a low symbol rate, maintaining total data rates similar to conventional single-carrier modulation schemes in the same bandwidth.

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, wireless networking and broadband internet access.

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. Channel equalization is simplified because OFDM may be viewed as using many slowly-modulated narrowband signals rather than one rapidly-modulated wideband signal. The low symbol rate makes the use of a guard interval between symbols affordable, making it possible to handle time-spreading and eliminate intersymbol interference (ISI). This mechanism also facilitates the design of single frequency networks (SFNs), where several adjacent transmitters send the same signal simultaneously at the same frequency, as the signals from multiple distant transmitters may be combined constructively, rather than interfering as would typically occur in a traditional single-carrier system.

Example of applications

The following list is a summary of existing OFDM based standards and products. For further details, see the Usage section at the end of the article.

Cable
- PEP via telephone lines.
- ADSL and VDSL broadband access via POTS copper wiring.
- Power line communication (PLC).
- Multimedia over Coax Alliance (MoCA) home networking.
- ITU-T G.hn, a standard which provides high-speed local area networking over existing home wiring (power lines, phone lines and coaxial cables).
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• DVB-C2, an enhanced version of the DVB-C digital cable TV standard.

Wireless
• The wireless LAN (WLAN) radio interfaces IEEE 802.11a, g, n and HIPERLAN/2.
• The digital radio systems DAB/EUREKA 147, DAB+, Digital Radio Mondiale, HD Radio, T-DMB and ISDB-TSB.
• The terrestrial digital TV systems DVB-T and ISDB-T.
• The terrestrial mobile TV systems DVB-H, T-DMB, ISDB-T and MediaFLO forward link.
• The cellular network’s FLASH-OFDM.
• The mobile broadband 3GPP Long Term Evolution air interface named High Speed OFDM Packet Access (HSOPA).
• The wireless MAN/fixed broadband wireless access (BWA) standard IEEE 802.16 (or WiMAX).
• The mobile broadband wireless access (MBWA) standards IEEE 802.20, IEEE 802.16e (Mobile WiMAX) and WiBro.
• The wireless personal area network (PAN) ultra-wideband (UWB) IEEE 802.15.3a implementation suggested by WiMedia Alliance.

Key features
The advantages and disadvantages listed below are further discussed in the Characteristics and principles of operation section below.

Summary of advantages
• Can easily adapt to severe channel conditions without complex equalization.
• Robust against narrow-band co-channel interference.
• Robust against intersymbol interference (ISI) and fading caused by multipath propagation.
• High spectral efficiency as compared to conventional modulation schemes, spread spectrum, etc.
• Efficient implementation using Fast Fourier Transform (FFT).
• Low sensitivity to time synchronization errors.
• Tuned sub-channel receiver filters are not required (unlike conventional FDM).
• Facilitates single frequency networks (SFNs); i.e., transmitter macrodiversity.

Summary of disadvantages
• Sensitive to Doppler shift.
• Sensitive to frequency synchronization problems.
• High peak-to-average-power ratio (PAPR), requiring linear transmitter circuitry, which suffers from poor power efficiency.
• Loss of efficiency caused by cyclic prefix/guard interval.
Characteristics and principles of operation

Orthogonality

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.

The orthogonality requires that the sub-carrier spacing is $\Delta f = \frac{k}{T_U}$ Hertz, where $T_U$ seconds is the useful symbol duration (the receiver side window size), and $k$ is a positive integer, typically equal to 1. Therefore, with $N$ sub-carriers, the total passband bandwidth will be $B = N\Delta f$ (Hz).

The orthogonality also 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.

A simple example: A useful symbol duration $T_U = 1$ ms would require a sub-carrier spacing of $\Delta f = \frac{1}{1000} = 1 \text{kHz}$ (or an integer multiple of that) for orthogonality. $N = 1,000$ sub-carriers would result in a total passband bandwidth of $N\Delta f = 1$ MHz. For this symbol time, the required bandwidth in theory according to Nyquist is $N/2T_U = 0.5$ MHz (i.e., half of the achieved bandwidth required by our scheme). If a guard interval is applied (see below), Nyquist bandwidth requirement would be even lower. The FFT would result in $N = 1,000$ samples per symbol. If no guard interval was applied, this would result in a base band complex valued signal with a sample rate of 1 MHz, which would require a baseband bandwidth of 0.5 MHz according to Nyquist. However, the passband RF signal is produced by multiplying the baseband signal with a carrier waveform (i.e., double-sideband quadrature amplitude-modulation) resulting in a passband bandwidth of 1 MHz. A single-side band (SSB) or vestigial sideband (VSB) modulation scheme would achieve almost half that bandwidth for the same symbol rate (i.e., twice as high spectral efficiency for the same symbol alphabet length). It is however more sensitive to multipath interference.

OFDM requires very accurate frequency synchronization between the receiver and the transmitter; with frequency deviation the sub-carriers will no longer be orthogonal, causing inter-carrier interference (ICI) (i.e., cross-talk between the sub-carriers). Frequency offsets are typically caused by mismatched transmitter and receiver oscillators, or by Doppler shift due to movement. While Doppler shift alone may be compensated for by the receiver, the situation is worsened when combined with multipath, as reflections will appear at various frequency offsets, which is much harder to correct. This effect typically worsens as speed increases\(^1\), and is an important factor limiting the use of OFDM in high-speed vehicles. Several techniques for ICI suppression are suggested, but they may increase the receiver complexity.

Implementation using the FFT algorithm

The orthogonality allows for efficient modulator and demodulator implementation using the FFT algorithm on the receiver side, and inverse FFT on the sender side. Although the principles and some of the benefits have been known since the 1960s, OFDM is popular for wideband communications today by way of low-cost digital signal processing components that can efficiently calculate the FFT.

Guard interval for elimination of intersymbol interference

One key principle of OFDM is that since low symbol rate modulation schemes (i.e., where the symbols are relatively long compared to the channel time characteristics) suffer less from intersymbol interference caused by multipath propagation, it is advantageous to transmit a number of low-rate streams in parallel instead of a single high-rate stream. Since the duration of each symbol is long, it is feasible to insert a guard interval between the OFDM
symbols, thus eliminating the intersymbol interference.

The guard interval also eliminates the need for a pulse-shaping filter, and it reduces the sensitivity to time synchronization problems.

A simple example: If one sends a million symbols per second using conventional single-carrier modulation over a wireless channel, then the duration of each symbol would be one microsecond or less. This imposes severe constraints on synchronization and necessitates the removal of multipath interference. If the same million symbols per second are spread among one thousand sub-channels, the duration of each symbol can be longer by a factor of a thousand (i.e., one millisecond) for orthogonality with approximately the same bandwidth. Assume that a guard interval of 1/8 of the symbol length is inserted between each symbol. Intersymbol interference can be avoided if the multipath time-spreading (the time between the reception of the first and the last echo) is shorter than the guard interval (i.e., 125 microseconds). This corresponds to a maximum difference of 37.5 kilometers between the lengths of the paths.

The cyclic prefix, which is transmitted during the guard interval, consists of the end of the OFDM symbol copied into the guard interval, and the guard interval is transmitted followed by the OFDM symbol. The reason that the guard interval consists of a copy of the end of the OFDM symbol is so that the receiver will integrate over an integer number of sinusoid cycles for each of the multipaths when it performs OFDM demodulation with the FFT.

**Simplified equalization**

The effects of frequency-selective channel conditions, for example fading caused by multipath propagation, can be considered as constant (flat) over an OFDM sub-channel if the sub-channel is sufficiently narrow-banded (i.e., if the number of sub-channels is sufficiently large). This makes equalization far simpler at the receiver in OFDM in comparison to conventional single-carrier modulation. The equalizer only has to multiply each detected sub-carrier (each Fourier coefficient) by a constant complex number, or a rarely changed value.

Our example: The OFDM equalization in the above numerical example would require one complex valued multiplication per subcarrier and symbol (i.e., $N = 1000$ complex multiplications per OFDM symbol; i.e., one million multiplications per second, at the receiver). The FFT algorithm requires $N \log_2 N = 10,000$ complex-valued multiplications per OFDM symbol (i.e., 10 million multiplications per second), at both the receiver and transmitter side. This should be compared with the corresponding one million symbols/second single-carrier modulation case mentioned in the example, where the equalization of 125 microseconds time-spreading using a FIR filter would require, in a naive implementation, 125 multiplications per symbol (i.e., 125 million multiplications per second). FFT techniques can be used to reduce the number of multiplications for an FIR equalizer to a number comparable with OFDM, at the cost of delay between reception and decoding which also becomes comparable with OFDM.

In a sense, improvements in FIR equalization using FFTs or partial FFTs leads mathematically closer to OFDM, but the OFDM technique is easier to understand and implement, and the sub-channels can be independently adapting in other ways than varying equalization coefficients, such as switching between different QAM constellation patterns and error-correction schemes to match individual sub-channel noise and interference characteristics.

Some of the sub-carriers in some of the OFDM symbols may carry pilot signals for measurement of the channel conditions\(^2\) \(^3\) (i.e., the equalizer gain and phase shift for each sub-carrier). Pilot signals and training symbols(Preamble_(communication)) may also be used for time synchronization (to avoid intersymbol interference, ISI), and frequency synchronization (to avoid inter-carrier interference, ICI, caused by Doppler shift).

If differential modulation such as DPSK or DQPSK is applied to each sub-carrier, equalization can be completely omitted, since these non-coherent schemes are insensitive to slowly changing amplitude and phase distortion.

OFDM was initially used for wire, and stationary wireless communications. However with increasing number of applications operating in highly mobile environment, the possibility of using OFDM for such purpose is also
Orthogonal frequency-division multiplexing

investigated. Over the last decade, several research have been done on how to equalize OFDM transmission over doubly selective channels[4][5][6].

Channel coding and interleaving

OFDM is invariably used in conjunction with channel coding (forward error correction), and almost always uses frequency and/or time interleaving.

Frequency (subcarrier) interleaving increases resistance to frequency-selective channel conditions such as fading. For example, when a part of the channel bandwidth fades, frequency interleaving ensures that the bit errors that would result from those subcarriers in the faded part of the bandwidth are spread out in the bit-stream rather than being concentrated. Similarly, time interleaving ensures that bits that are originally close together in the bit-stream are transmitted far apart in time, thus mitigating against severe fading as would happen when travelling at high speed.

However, time interleaving is of little benefit in slowly fading channels, such as for stationary reception, and frequency interleaving offers little to no benefit for narrowband channels that suffer from flat-fading (where the whole channel bandwidth fades at the same time).

The reason why interleaving is used on OFDM is to attempt to spread the errors out in the bit-stream that is presented to the error correction decoder, because when such decoders are presented with a high concentration of errors the decoder is unable to correct all the bit errors, and a burst of uncorrected errors occurs. A similar design of audio data encoding makes compact disc (CD) playback robust.

A classical type of error correction coding used with OFDM-based systems is convolutional coding, often concatenated with Reed-Solomon coding. Usually, additional interleaving (on top of the time and frequency interleaving mentioned above) in between the two layers of coding is implemented. The choice for Reed-Solomon coding as the outer error correction code is based on the observation that the Viterbi decoder used for inner convolutional decoding produces short errors bursts when there is a high concentration of errors, and Reed-Solomon codes are inherently well-suited to correcting bursts of errors.

Newer systems, however, usually now adopt near-optimal types of error correction codes that use the turbo decoding principle, where the decoder iterates towards the desired solution. Examples of such error correction coding types include turbo codes and LDPC codes, which perform close to the Shannon limit for the Additive White Gaussian Noise (AWGN) channel. Some systems that have implemented these codes have concatenated them with either Reed-Solomon (for example on the MediaFLO system) or BCH codes (on the DVB-S2 system) to improve upon an error floor inherent to these codes at high signal-to-noise ratios.

Adaptive transmission

The resilience to severe channel conditions can be further enhanced if information about the channel is sent over a return-channel. Based on this feedback information, adaptive modulation, channel coding and power allocation may be applied across all sub-carriers, or individually to each sub-carrier. In the latter case, if a particular range of frequencies suffers from interference or attenuation, the carriers within that range can be disabled or made to run slower by applying more robust modulation or error coding to those sub-carriers.

The term discrete multitone modulation (DMT) denotes OFDM based communication systems that adapt the transmission to the channel conditions individually for each sub-carrier, by means of so called bit-loading. Examples are ADSL and VDSL.

The upstream and downstream speeds can be varied by allocating either more or fewer carriers for each purpose. Some forms of rate-adaptive DSL use this feature in real time, so that the bitrate is adapted to the co-channel interference and bandwidth is allocated to whichever subscriber needs it most.
OFDM extended with multiple access

OFDM in its primary form is considered as a digital modulation technique, and not a multi-user channel access method, since it is utilized for transferring one bit stream over one communication channel using one sequence of OFDM symbols. However, OFDM can be combined with multiple access using time, frequency or coding separation of the users.

In Orthogonal Frequency Division Multiple Access (OFDMA), frequency-division multiple access is achieved by assigning different OFDM sub-channels to different users. OFDMA supports differentiated quality of service by assigning different number of sub-carriers to different users in a similar fashion as in CDMA, and thus complex packet scheduling or Media Access Control schemes can be avoided. OFDMA is used in:

- the mobility mode of the IEEE 802.16 Wireless MAN standard, commonly referred to as WiMAX,
- the IEEE 802.20 mobile Wireless MAN standard, commonly referred to as MBWA,
- the 3GPP Long Term Evolution (LTE) fourth generation mobile broadband standard downlink. The radio interface was formerly named High Speed OFDM Packet Access (HSOPA), now named Evolved UMTS Terrestrial Radio Access (E-UTRA).
- the now defunct Qualcomm/3GPP2 Ultra Mobile Broadband (UMB) project, intended as a successor of CDMA2000, but replaced by LTE.

OFDMA is also a candidate access method for the IEEE 802.22 Wireless Regional Area Networks (WRAN). The project aims at designing the first cognitive radio based standard operating in the VHF-low UHF spectrum (TV spectrum).

In Multi-carrier code division multiple access (MC-CDMA), also known as OFDM-CDMA, OFDM is combined with CDMA spread spectrum communication for coding separation of the users. Co-channel interference can be mitigated, meaning that manual fixed channel allocation (FCA) frequency planning is simplified, or complex dynamic channel allocation (DCA) schemes are avoided.

Space diversity

In OFDM based wide area broadcasting, receivers can benefit from receiving signals from several spatially-dispersed transmitters simultaneously, since transmitters will only destructively interfere with each other on a limited number of sub-carriers, whereas in general they will actually reinforce coverage over a wide area. This is very beneficial in many countries, as it permits the operation of national SFNs, where many transmitters send the same signal simultaneously over the same channel frequency. SFNs utilise the available spectrum more effectively than conventional multi-frequency broadcast networks (MFN), where program content is replicated on different carrier frequencies. SFNs also result in a diversity gain in receivers situated midway between the transmitters. The coverage area is increased and the outage probability decreased in comparison to an MFN, due to increased received signal strength averaged over all sub-carriers.

Although the guard interval only contains redundant data, which means that it reduces the capacity, some OFDM-based systems, such as some of the broadcasting systems, deliberately use a long guard interval in order to allow the transmitters to be spaced farther apart in an SFN, and longer guard intervals allow larger SFN cell-sizes. A rule of thumb for the maximum distance between transmitters in an SFN is equal to the distance a signal travels during the guard interval — for instance, a guard interval of 200 microseconds would allow transmitters to be spaced 60 km apart.

A single frequency network is a form of transmitter macrodiversity. The concept can be further utilized in dynamic single-frequency networks (DSFN), where the SFN grouping is changed from timeslot to timeslot.

OFDM may be combined with other forms of space diversity, for example antenna arrays and MIMO channels. This is done in the IEEE802.11n Wireless LAN standard.


Linear transmitter power amplifier

An OFDM signal exhibits a high peak-to-average power ratio (PAPR) because the independent phases of the sub-carriers mean that they will often combine constructively. Handling this high PAPR requires:

• a high-resolution digital-to-analogue converter (DAC) in the transmitter
• a high-resolution analogue-to-digital converter (ADC) in the receiver
• a linear signal chain.

Any non-linearity in the signal chain will cause intermodulation distortion that

• raises the noise floor
• may cause inter-carrier interference
• generates out-of-band spurious radiation.

The linearity requirement is demanding, especially for transmitter RF output circuitry where amplifiers are often designed to be non-linear in order to minimise power consumption. In practical OFDM systems a small amount of peak clipping is allowed to limit the PAPR in a judicious trade-off against the above consequences. However, the transmitter output filter which is required to reduce out-of-band spurs to legal levels has the effect of restoring peak levels that were clipped, so clipping is not an effective way to reduce PAPR.

Although the spectral efficiency of OFDM is attractive for both terrestrial and space communications, the high PAPR requirements have so far limited OFDM applications to terrestrial systems.

Idealized system model

This section describes a simple idealized OFDM system model suitable for a time-invariant AWGN channel.

Transmitter

An OFDM carrier signal is the sum of a number of orthogonal sub-carriers, with baseband data on each sub-carrier being independently modulated commonly using some type of quadrature amplitude modulation (QAM) or phase-shift keying (PSK). This composite baseband signal is typically used to modulate a main RF carrier.

\( s[n] \) is a serial stream of binary digits. By inverse multiplexing, these are first demultiplexed into \( N \) parallel streams, and each one mapped to a (possibly complex) symbol stream using some modulation constellation (QAM, PSK, etc.). Note that the constellations may be different, so some streams may carry a higher bit-rate than others.

An inverse FFT is computed on each set of symbols, giving a set of complex time-domain samples. These samples are then quadrature-mixed to passband in the standard way. The real and imaginary components are first converted to the analogue domain using digital-to-analogue converters (DACs); the analogue signals are then used to modulate cosine and sine waves at the carrier frequency, \( f_c \), respectively. These signals are then summed to give the transmission signal, \( s(t) \).
Receiver

The receiver picks up the signal $r(t)$, which is then quadrature-mixed down to baseband using cosine and sine waves at the carrier frequency. This also creates signals centered on $2f_c$, so low-pass filters are used to reject these. The baseband signals are then sampled and digitised using analogue-to-digital converters (ADCs), and a forward FFT is used to convert back to the frequency domain.

This returns $N$ parallel streams, each of which is converted to a binary stream using an appropriate symbol detector. These streams are then re-combined into a serial stream, $\hat{s}[n]$, which is an estimate of the original binary stream at the transmitter.

Mathematical description

If $N$ sub-carriers are used, and each sub-carrier is modulated using $M$ alternative symbols, the OFDM symbol alphabet consists of $M^N$ combined symbols.

The low-pass equivalent OFDM signal is expressed as:

$$\nu(t) = \sum_{k=0}^{N-1} X_k e^{j2\pi k t / T}, \quad 0 \leq t < T,$$

where $\{X_k\}$ are the data symbols, $N$ is the number of sub-carriers, and $T$ is the OFDM symbol time. The sub-carrier spacing of $\frac{1}{T}$ makes them orthogonal over each symbol period; this property is expressed as:

$$\frac{1}{T} \int_0^T \left( e^{-j2\pi k_1 t / T} \right)^* \left( e^{j2\pi k_2 t / T} \right) dt = \delta_{k_1 k_2} \delta$$

where $\cdot^*$ denotes the complex conjugate operator and $\delta$ is the Kronecker delta.

To avoid intersymbol interference in multipath fading channels, a guard interval of length $T_g$ is inserted prior to the OFDM block. During this interval, a cyclic prefix is transmitted such that the signal in the interval $-T_g \leq t < 0$ equals the signal in the interval $(T-T_g) \leq t < T$. The OFDM signal with cyclic prefix is thus:

$$\nu(t) = \sum_{k=0}^{N-1} X_k e^{j2\pi k t / T}, \quad -T_g \leq t < T$$

The low-pass signal above can be either real or complex-valued. Real-valued low-pass equivalent signals are typically transmitted at baseband—wireline applications such as DSL use this approach. For wireless applications, the low-pass signal is typically complex-valued; in which case, the transmitted signal is up-converted to a carrier frequency $f_c$. In general, the transmitted signal can be represented as:
$$s(t) = \Re \left\{ \sum_{k=0}^{N-1} |X_k| \cos \left( 2\pi f_c + k/T \right) t + \arg(|X_k|) \right\}$$

### Usage

**OFDM system comparison table**

Key features of some common OFDM based systems are presented in the following table.

<table>
<thead>
<tr>
<th>Standard name</th>
<th>DAB Eureka 147</th>
<th>DVB-T</th>
<th>DVB-H</th>
<th>DMR-T/H</th>
<th>DVB-T2</th>
<th>IEEE 802.11a</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency range</strong></td>
<td>174–240</td>
<td>1,452–1,492</td>
<td>470–862</td>
<td>470–862</td>
<td>470–862</td>
<td>4,915–5,825</td>
</tr>
<tr>
<td>of today’s equipment</td>
<td>MHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Channel spacing</strong></td>
<td>1.712</td>
<td>6, 7, 8</td>
<td>5, 6, 7, 8</td>
<td>8</td>
<td>1.7, 5, 6, 7, 8, 10</td>
<td>20</td>
</tr>
<tr>
<td><strong>B (MHz)</strong></td>
<td>Mode I: 2k</td>
<td>Mode II: 512</td>
<td>Mode III: 256</td>
<td>Mode IV: 1k</td>
<td>1k, 2k, 4k, 8k, 16k, 32k</td>
<td>64</td>
</tr>
<tr>
<td><strong>Number of</strong></td>
<td>2K mode: 1,705</td>
<td>1,705, 3,409, 6,817</td>
<td>1 (single-carrier)</td>
<td>1k, 2k, 4k, 8k, 16k, 32k</td>
<td>853-27,841 (1K normal to 32K extended carrier mode)</td>
<td>52</td>
</tr>
<tr>
<td><strong>non-silent sub-carriers, N</strong></td>
<td>Mode I: 1,536</td>
<td>Mode II: 384</td>
<td>Mode III: 192</td>
<td>Mode IV: 768</td>
<td>1 (multi-carrier)</td>
<td></td>
</tr>
<tr>
<td><strong>Sub-carrier</strong></td>
<td>4/π-DQPSK</td>
<td>QPSK[7], 16QAM or 64QAM</td>
<td>QPSK[7], 16QAM or 64QAM</td>
<td>4QAM[7], [8]</td>
<td>QPSK, 16QAM, 64QAM, 256QAM</td>
<td>BPSK, QPSK[7], 16QAM or 64QAM</td>
</tr>
<tr>
<td><strong>modulation scheme</strong></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td><strong>Useful symbol</strong></td>
<td>Mode I: 1,000</td>
<td>Mode II: 250</td>
<td>Mode III: 125</td>
<td>Mode IV: 500</td>
<td>2K mode: 224</td>
<td>112-3,584 (1K to 32K mode on 8 MHz channel)</td>
</tr>
<tr>
<td><strong>length, T(U)</strong></td>
<td>2K mode: 224</td>
<td>224, 448, 896</td>
<td>500 (multi-carrier)</td>
<td>112-3,584 (1K to 32K mode on 8 MHz channel)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>(μs)</strong></td>
<td>8K mode: 896</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>Additional guard</strong></td>
<td>24.6% (all modes)</td>
<td>1/4, 1/8, 1/16, 1/32</td>
<td>1/4, 1/8, 1/16, 1/32</td>
<td>1/4, 1/8, 1/16, 1/32</td>
<td>1/4, 1/8, 1/16, 1/32</td>
<td></td>
</tr>
<tr>
<td><strong>interval, T(G)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>(fraction of T(U))</strong></td>
<td>Mode I: 1,000</td>
<td>Mode II: 4,000</td>
<td>Mode III: 8,000</td>
<td>Mode IV: 2,000</td>
<td>2K mode: 4,464</td>
<td>279-8,929 (32K down to 1K mode)</td>
</tr>
<tr>
<td><strong>Sub-carrier</strong></td>
<td>2K mode: 4,464</td>
<td>4,464, 2,232, 1,116</td>
<td>8 M (single-carrier)</td>
<td>279-8,929 (32K down to 1K mode)</td>
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<tr>
<td><strong>spacing</strong></td>
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</tr>
<tr>
<td><strong>Δf = f_c / T(G)</strong></td>
<td>0.576–1.152</td>
<td>4.98–31.67 (typically 24.13)</td>
<td>3.7–23.8</td>
<td>4.81–32.49</td>
<td>Typically 35.4</td>
<td></td>
</tr>
<tr>
<td><strong>Net bit rate, R</strong></td>
<td>0.576–1.152</td>
<td>4.98–31.67 (typically 24.13)</td>
<td>3.7–23.8</td>
<td>4.81–32.49</td>
<td>Typically 35.4</td>
<td></td>
</tr>
<tr>
<td><strong>(Mbit/s)</strong></td>
<td>0.576–1.152</td>
<td>4.98–31.67 (typically 24.13)</td>
<td>3.7–23.8</td>
<td>4.81–32.49</td>
<td>Typically 35.4</td>
<td></td>
</tr>
<tr>
<td><strong>Link spectral</strong></td>
<td>0.34–0.67</td>
<td>0.62–4.0 (Typ 3.0)</td>
<td>0.62–4.0</td>
<td>0.60–4.1</td>
<td>0.87-6.65</td>
<td>0.30–2.7</td>
</tr>
<tr>
<td><strong>efficiency R/B</strong></td>
<td></td>
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<tr>
<td><strong>(bit/s/Hz)</strong></td>
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<tr>
<td>Inner FEC</td>
<td>Conv coding with Equal error protection code rates $\frac{1}{4}, \frac{3}{8}, \frac{4}{9}, \frac{1}{2}, \frac{4}{7}, \frac{2}{3}, \frac{3}{4}, \frac{4}{5}$ Unequal error protection with av. code rates of ~0.34, 0.41, 0.50, 0.60, and 0.75</td>
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<td>-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
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<tr>
<td>Outer FEC (if any)</td>
<td>Optional RS (120, 110, t = 5) RS (204, 188, t=8) RS (204, 188, t=8) + MPE-FEC BCH code (762, 752) BCH code</td>
<td></td>
<td></td>
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<tr>
<td>Maximum travelling speed (km/h)</td>
<td>200–600 53–185 depends on transmission frequency</td>
<td></td>
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</tr>
<tr>
<td>Time interleaving depth (ms)</td>
<td>384 0.6–3.5 0.6–3.5 200–500 up to 250 (500 with extension frame)</td>
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<tr>
<td>Adaptive transmission (if any)</td>
<td>None None None None</td>
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<tr>
<td>Multiple access method (if any)</td>
<td>None None None None</td>
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</tr>
<tr>
<td>Typical source coding</td>
<td>192 kbit/s MPEG2 Audio layer 2 2–18 Mbit/s Standard - HDTV H.264 or MPEG2 H.264 Not defined (Video: MPEG-2, H.264 and/or AVS Audio: MP2 or AC-3) H.264 or MPEG2</td>
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</tbody>
</table>

**ADSL**

OFDM is used in ADSL connections that follow the G.DMT (ITU G.992.1) standard, in which existing copper wires are used to achieve high-speed data connections.

Long copper wires suffer from attenuation at high frequencies. The fact that OFDM can cope with this frequency selective attenuation and with narrow-band interference are the main reasons it is frequently used in applications such as ADSL modems. However, DSL cannot be used on every copper pair; interference may become significant if more than 25% of phone lines coming into a central office are used for DSL.

For experimental amateur radio applications, users have even hooked up commercial off-the-shelf ADSL equipment to radio transceivers which simply shift the bands used to the radio frequencies the user has licensed.