OFDM for Mobile Data Communications

Definition

Orthogonal frequency division multiplexing (OFDM) is a communications technique that divides a communications channel into a number of equally spaced frequency bands. A subcarrier carrying a portion of the user information is transmitted in each band. Each subcarrier is orthogonal (independent of each other) with every other subcarrier, differentiating OFDM from the commonly used frequency division multiplexing (FDM).

Overview

This tutorial describes OFDM and its application to mobile communications. OFDM is a modulation and multiple-access technique that has been explored for more than 20 years. Only recently has it been finding its way into commercial communications systems, as Moore's Law has driven down the cost of the signal processing that is needed to implement OFDM–based systems.

OFDM, or multitone modulation as it is sometimes called, is presently used in a number of commercial wired and wireless applications. On the wired side, it is used for a variant of digital subscriber line (DSL). For wireless, OFDM is the basis for several television and radio broadcast applications, including the European digital broadcast television standard, as well as digital radio in North America. OFDM is also used in several fixed wireless systems and wireless local-area network (LAN) products. A system based on OFDM has been developed to deliver mobile broadband data service at data rates comparable to those of wired services, such as DSL and cable modems.

It is important that the overall system design be well matched to the service profiles to maximize the performance of the system and balance the ultimate user experience it provides relative to the cost to the operator. OFDM enables the creation of a very flexible system architecture that can be used efficiently for a wide range of services, including voice and data. For any mobile system to create a rich user experience, it must provide ubiquitous, fast, and user-friendly connectivity. OFDM has several unique properties that make it especially well suited to handle the challenging environmental conditions experienced by mobile wireless data applications.

Topics

1. Characteristics and Evolution of Data Communications for a Mobile Environment

Cellular and personal communications service (PCS) communications systems have historically been designed with voice traffic in mind. The patterns associated with voice communications are well known, having been observed since the invention and widespread use of the telephone. Voice can be characterized as relatively predictable, with each party talking about half the time in an interactive manner. The statistics of call duration and time of day are well understood, allowing traffic engineers to use a standard methodology to estimate the amount of capacity needed in a communications system. The wireline telephone network has been engineered in a hierarchical fashion using large circuit switches to efficiently connect one voice user to another. The physical circuit over which a call is made is held open for the entire duration of a call, hence the term circuit switching. Voice in wireline and mobile settings have similar characteristics. Existing cellular telephone systems have therefore been designed in a similar way and optimized to efficiently provide voice service.

Data traffic differs from voice in at least three important ways:

1. First, data traffic is much more unpredictable than voice traffic. Data is characterized as bursty, meaning that there is significant variability in when the traffic arrives, the rate at which it arrives, and the number of bits in the messages.

2. Second, data has very different requirements in terms of reliability. Whereas voice is very robust and capable of being understood even in a noisy environment with a high bit-error rate (BER) approaching one percent, data applications require extremely reliable delivery, with virtually no tolerance for bit errors. Because some bit errors are unavoidable on wireless links, it is important that fast and efficient recovery schemes are implemented to get the correct data bits to the application. A combination of forward error correction (FEC) and fast acknowledgements (an automatic retransmission request [ARQ]) satisfies this need. Powerful FEC is employed to dramatically reduce the BER, and an ARQ is used to guarantee reliable delivery.

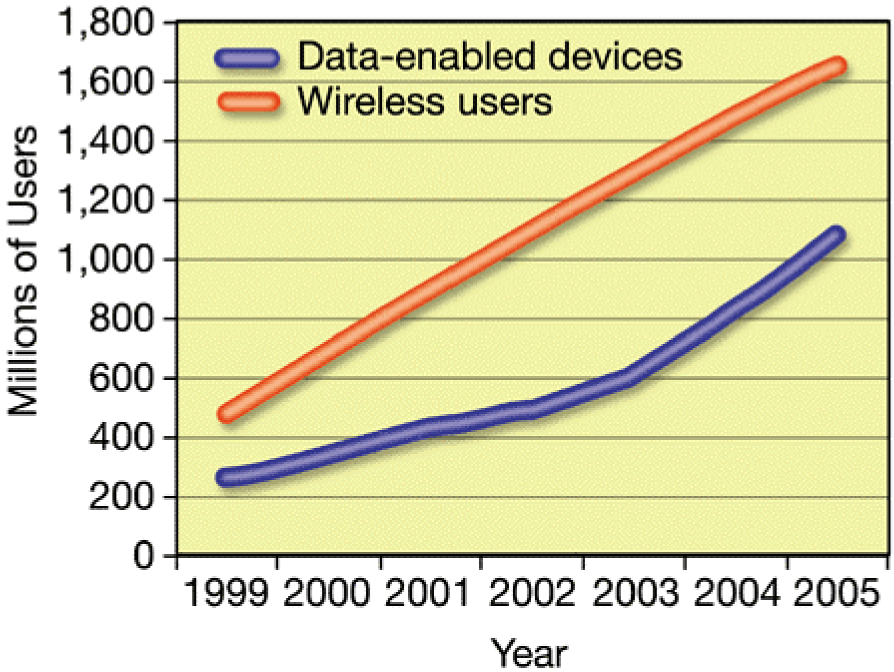
3. Third, data traffic encompasses a much different and wider range of services than voice. Different types of services have different requirements along several dimensions. A data service can be characterized by its importance or priority. This is determined by the quality of service (QoS) that is required, which can be measured by the amount of delay that a user is willing to tolerate, and the reliability required. A service provider may offer differing service rates, or classes of service (CoS), accordingly. Premium service users may be given priority over best-effort users, whose traffic is sent if there is capacity available at the time. The data rate that is required and granted to a user is another dimension for a data service. A user may have a service-level agreement (SLA), which guarantees a certain minimum rate and allows a maximum or average rate over some period of time. A final aspect of a data service is latency, or response time. This determines the degree of interactivity that can be achieved, which is a measure of how quickly channel resources can be assigned at the request of a user.

Many feel that data services differ from voice in one other way, which is related to the variability in capacity demanded by the end user. If data users are allowed to consume as much bandwidth as they can, provided that there are no higher-priority users contending for resources, a system will tend to always be in a state of high utilization. The admission control mechanism, which governs how users access the system and are allocated resources, becomes a potential bottleneck under such circumstances. To provide low latencies in a wireless environment, where errors are unavoidable and packets must be retransmitted, it is necessary for a system to employ a fast ARQ capability so that packets received in error can be quickly retransmitted. Fast ARQ, in turn, requires that the user's access to the system be quick in order to transmit acknowledgements upon the receipt of correct packets. Systems employing a contention-based admission control generally exhibit ever-growing latencies as utilization increases and cannot support a fast ARQ capability. A well-designed system employing scheduled, non-contention-based access can yield much lower latency and support rapid ARQs.

Today's data traffic is primarily driven by wireline users and generated by a broad range of sources and applications, including Internet use, electronic messaging, file transfer, and, to some degree, voice traffic such as voice over Internet protocol (VoIP) (using primarily desktop and portable computers). The transmission control protocol (TCP)/Internet protocol (IP) suite, which is the data-transmission protocol used for the Internet, is the most widely used and governs the bulk of all data traffic.

In the future, the number of devices generating data traffic is expected to skyrocket by an order of magnitude. Information appliances and other data-centric wireless and consumer products will fuel this growth, leveraging the inherent value that mobility provides.

Figure 1. Wireless User versus Data-Device Growth Sources: Cahners In-Stat, Goldman Sachs, IDC, Lehman Brothers, Semico



The types and mix of applications and services used will also change over time as the mix of devices changes, with more interactive applications such as voice, gaming, two-way messaging, and even video joining less-interactive applications such as streaming audio and video and traditional Web browsing. Much of this traffic will go over wireless data networks.

The true potential for ubiquitous wireless data communications can be unleashed when end-user devices efficiently support native TCP/IP connectivity, without the need for special translators and filters. Mobile wireless communications has traditionally posed a difficult performance challenge for TCP/IP protocols. TCP was designed and optimized around reliable wireline links, where BERs and packet-error rates are substantially lower than that typically achievable via wireless. When TCP encounters dropped or lost packets, it assumes that there is congestion on the link, but not that the link itself is unreliable. Congestion is handled by reducing the information rate at which the sender is allowed to transmit. By interpreting the unavoidable errors that occur in a wireless environment as congestion, the effective data rate seen by the end user is reduced. This is further compounded by the fact that the initial data rate at the start of a TCP session is low—far below the ultimate peak rate—and gradually builds over time as the systems figure out where the peak rate is. This slow-start aspect of TCP can dramatically add to latencies as the link is throttled down due to errors and then slowly ramped back up.

In summary, there is a much wider range of requirements and characteristics for data communications than there is for voice. This variability prohibits data from being efficiently carried over the hierarchical networks designed for voice traffic, whether wireline or wireless. Mobile data systems face additional challenges as a result of the vagaries of the wireless environment.

2. Overview of the Wireless Environment

Mobile cellular wireless systems operate under harsh and challenging channel conditions. The wireless channel is distinct and much more unpredictable than the wireline channel because of factors such as multipath and shadow fading, Doppler spread, and time dispersion or delay spread. These factors are all related to variability that is introduced by the mobility of the user and the wide range of environments that may be encountered as a result.

Multipath is a phenomenon that occurs as a transmitted signal is reflected by objects in the environment between the base station and a user. These objects can be buildings, trees, hills, or even trucks and cars. The reflected signals arrive at the receiver with random phase offsets, because each reflection generally follows a different path to reach the user's receiver. The result is random signal fades as the reflections destructively (and constructively) superimpose on one another, which effectively cancels part of the signal energy for brief periods of time. The degree of cancellation, or fading, will depend on the delay spread of the reflected signals, as embodied by their relative phases, and their relative power. *Figure 2* shows the arrival of a signal and two multipath components.

Figure 2. Example of Time-Delayed Multipath Signals

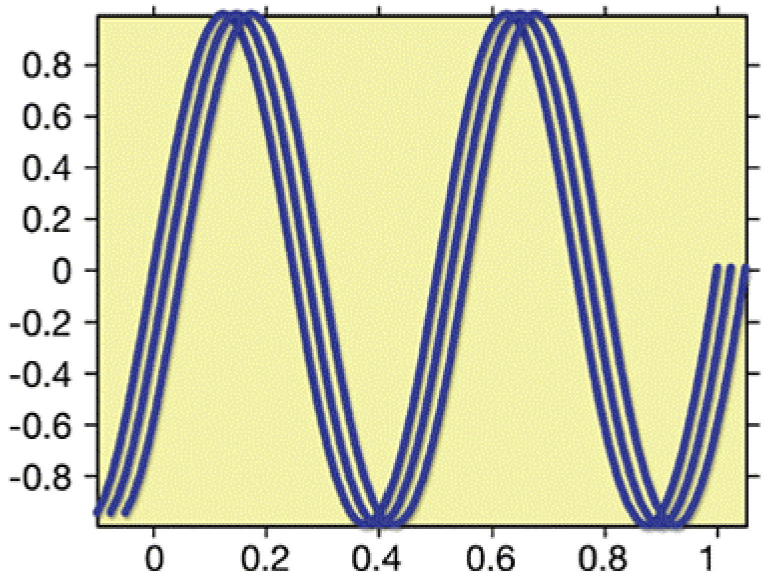
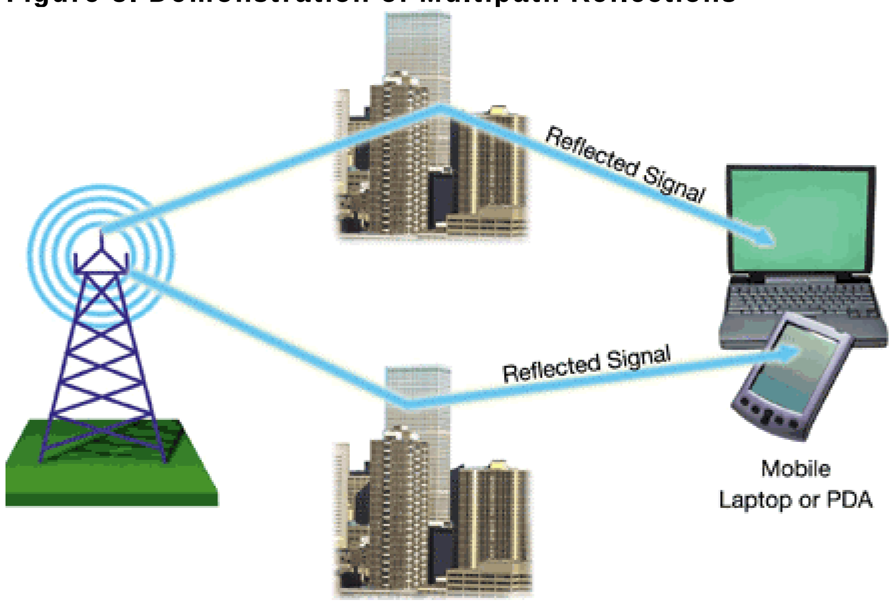


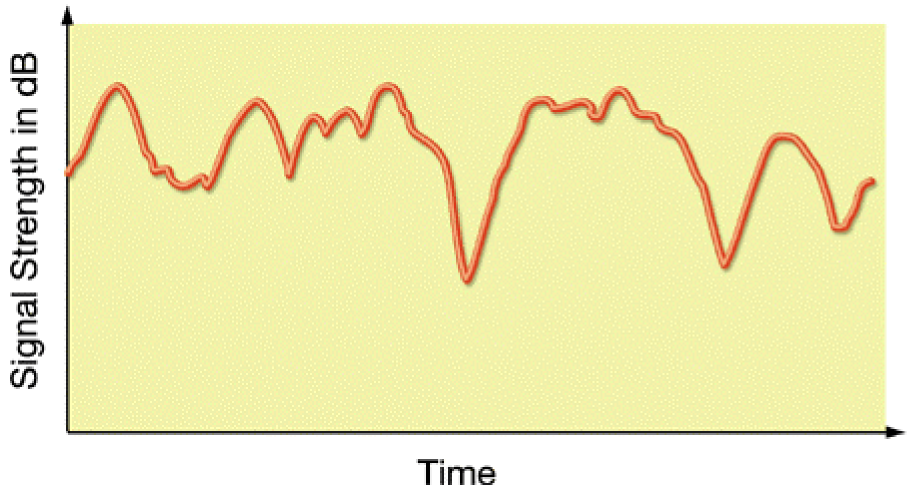
Figure 3. Demonstration of Multipath Reflections



Time dispersion represents distortion to the signal and is manifested by the spreading in time of the modulation symbols. This occurs when the channel is band-limited, or, in other words, when the coherence bandwidth of the channel is smaller than the modulation bandwidth. Time dispersion leads to intersymbol interference, or ISI, where the energy from one symbol spills over into another symbol, and, as a result, the BER is increased. It also leads to fading.

In many instances, the fading due to multipath will be frequency selective, randomly affecting only a portion of the overall channel bandwidth at any given time. Frequency selective fading occurs when the channel introduces time dispersion and when the delay spread exceeds the symbol period. When there is no dispersion and the delay spread is less than the symbol period, the fading will be flat, thereby affecting all frequencies in the signal equally. Flat fading can lead to deep fades of more than 30 decibels (dB).

Figure 4. Demonstration of Time-Varying Fading



Doppler spread describes the random changes in the channel introduced as a result of a user's mobility and the relative motion of objects in the channel. Doppler has the effect of shifting, or spreading, the frequency components of a signal. The coherence time of the channel is the inverse of the Doppler spread and is a measure of the speed at which the channel characteristics change. This in effect determines the rate at which fading occurs. When the rate of change of the channel is higher than the modulated symbol rate, fast fading occurs. Slow fading, on the other hand, occurs when the channel changes are slower than the symbol rate.

The statistics describing the fading signal amplitude are frequently characterized as either Rayleigh or Ricean. Rayleigh fading occurs when there is no line of sight (LOS) component present in the received signal. If there is a LOS component present, the fading follows a Ricean distribution. There is frequently no direct LOS path to a mobile, because the very nature of mobile communications means that mobiles can be in a building or behind one or other obstructions. This leads to Rayleigh fading but also results in a shadow loss. These conditions, along with the inherent variation in signal strength caused by changes in the distance between a mobile and cell site, result in a large dynamic range of signals, which can easily be as much as 70 dB.

In addition to the aforementioned channel impairments, spectrum is a scarce resource for wireless systems, and thus is reused within cellular systems. This means that the same frequencies are allocated to each cell, or to a cluster of cells, and are shared. This increases the overall system capacity at the expense of increased potential for interference within a cell and between cells as each channel is reused throughout the system. This generally results in cellular systems being interference-limited.

3. Overview of Traditional Mobile Wireless Systems

All modern mobile wireless systems employ a variety of techniques to combat the aforementioned effects. Some techniques are more effective than others, with the effectiveness depending on the air-interface and the system-architecture approach taken to satisfy the requirements of the services being offered. As mobile systems evolved from analog to digital, more sophisticated signal-processing techniques have been employed to overcome the wireless environment. These techniques include equalization, channel or error-correction coding, spread spectrum, interleaving, and diversity.

Diversity has long been used to help mitigate the multipath-induced fading that results from users' mobility. The simplest diversity technique, spatial diversity, involves the use of two or more receive antennae at a base station that are separated by some distance, say on the order of five to 10 wavelengths. The signal from the mobile will generally follow separate paths to each antenna. This relatively low-cost approach yields significant performance improvement by taking advantage of the statistical likelihood that the paths are not highly correlated with each other. When one antenna is in a fade, the other one will generally not be.

Spread spectrum systems employ a form of diversity called frequency diversity. Here the signal is spread over a much larger bandwidth than is needed for transmission and is typically greater than the coherence bandwidth of the channel. A wideband signal is more resistant to the effect of frequency selective fading than is a narrowband signal, because only a relatively small portion of the overall bandwidth use is likely to experience a fade at any given time. There are two forms of spread spectrum, code division multiple access (CDMA) and frequency hopping (FH).

CDMA systems, such as those used in interim standard (IS)–95 and third-generation (3G) wideband CDMA (WCDMA), mix the base-band information stream with a much higher rate pseudorandom spreading sequence code prior to transmission. This effectively increases the signal bandwidth. As a result, CDMA systems are termed spread spectrum. The spreading of the signal provides processing gain, which is used to limit the effects of multipath and Doppler fading, and allows the same frequency spectrum to be used by each user in each cell, provided that the transmitted power of every user is limited to only what is needed for acceptable reception. The amount of processing gain is determined by the ratio of the spread bandwidth to the bandwidth of an individual user's data stream.

Each user is assigned a unique spreading code when they have information to send. The same frequencies can be used by each user, because the receiver, which is listening for that user's specific code, is able to effectively ignore other users' signals as long as the codes are orthogonal. A problem that CDMA systems have is that the code sequences are not truly orthogonal in the presence of multipath delay spread. This results in interference between users within a cell. Called multiple access interference, it ultimately limits the capacity of the cell.

CDMA systems also employ time diversity. The multipath signals that are received can be time and phase adjusted so that they can be added together as long as the delay is more than one code symbol or chip time. This occurs in what is called a RAKE receiver.

Spread spectrum systems provide the further performance advantage of interference averaging, which is achieved as the user's signal occupies the entire system bandwidth—either through spreading or hopping. A CDMA system spreads out any interference uniformly over the entire band, making it appear as a small increase in the overall noise floor, while a frequency hopping system averages interference by minimizing the time when a user and interferer occupy the same frequency. In a cellular system, the majority of interference comes from other users rather than from external sources. Although more than half of the interference present in a CDMA cell is due to the users in that cell (rather than from other cells), the interference is still effectively averaged over all users so that no particular user is disproportionately disadvantaged.

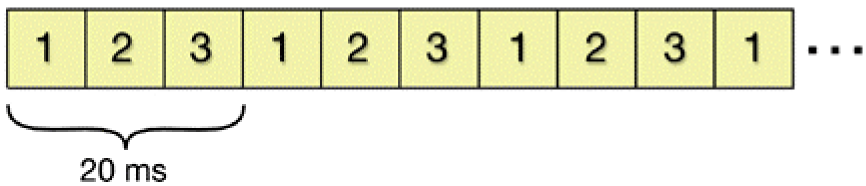
Interference averaging enables a system to be radio frequency (RF) engineered for the average interference experienced rather than the worst-case interference experienced, which allows a higher degree of frequency reuse to be used. This increases the overall system capacity.

Systems based on CDMA are very complex, with intensive signal processing required to implement them. Fast and accurate power-control loops must be used so that the signal from one user does not drown out the signals from other users, and each cell must be tightly synchronized. Errors in power control and time synchronization will result in reduced capacity and system performance.

Equalization is a technique used to overcome the effects of ISI resulting from time dispersion in the channel. Implemented at the receiver, the equalizer attempts to correct for the amplitude and phase distortions that occur in the channel. These distortions change with time, because the channel response is time varying. The equalizer must therefore adapt to, or track, the changing channel response to eliminate the ISI. The equalizer is fed a fixed-length training sequence at the start of each transmission, which enables it to characterize the channel at that time. A training sequence may also be sent periodically to maintain the equalizer's characterization of the channel.

Systems based on time division multiple access (TDMA), such as IS–136 and Global System for Mobile Communications (GSM) typically must use equalizers because their modulation symbol rate exceeds the coherence bandwidth of the channel (i.e., they operate in band-limited channels). The TDMA system divides the available spectrum into a number of equal bandwidth channels, and then subdivides each channel into timeslots according to a framing structure. The frame structure defines the duration of each time slot and how often they are repeated. *Figure 5* shows an example of a TDMA structure with a 20-millisecond frame consisting of three time slots.

Figure 5. TDMA Frame Structure Showing Recurring Slots

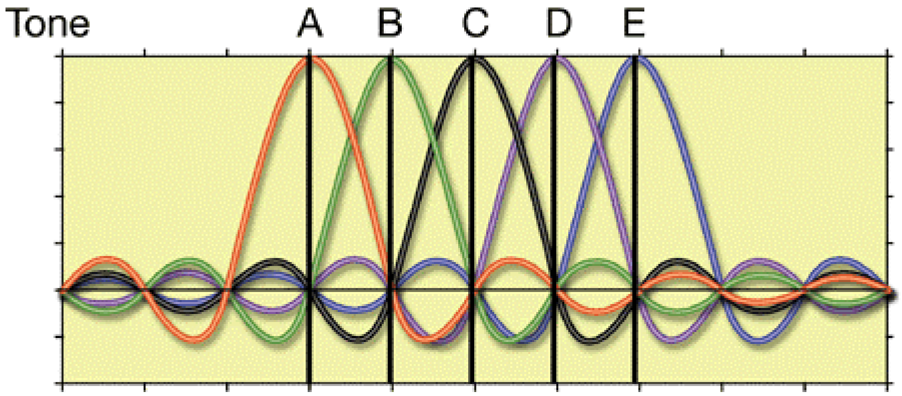


TDMA systems assign one or more time slots to a user for transmission. There is typically some guard time included between time slots to allow for time tracking errors at the mobile station. The use of equalizers adds to the complexity and costs of the TDMA systems, since equalization requires significant amounts of signal-processing power. The need to transmit a fixed sequence of training bits also adds overhead to the communications. Unlike CDMA–based systems, TDMA systems cannot use every frequency in every cell because of co-channel interference, and therefore need to be frequency planned. TDMA systems also have less inherent immunity against multipath fading than CDMA systems, because they use a much narrower signal bandwidth. On the plus side, TDMA users within a cell are orthogonal to each other, because they transmit at different times. Therefore, there is no intra-cell interference.

4. OFDM for Mobile Communications

OFDM represents a different system-design approach. It can be thought of as a combination of modulation and multiple-access schemes that segments a communications channel in such a way that many users can share it. Whereas TDMA segments are according to time and CDMA segments are according to spreading codes, OFDM segments are according to frequency. It is a technique that divides the spectrum into a number of equally spaced tones and carries a portion of a user's information on each tone. A tone can be thought of as a frequency, much in the same way that each key on a piano represents a unique frequency. OFDM can be viewed as a form of frequency division multiplexing (FDM), however, OFDM has an important special property that each tone is orthogonal with every other tone. FDM typically requires there to be frequency guard bands between the frequencies so that they do not interfere with each other. OFDM allows the spectrum of each tone to overlap, and because they are orthogonal, they do not interfere with each other. By allowing the tones to overlap, the overall amount of spectrum required is reduced.

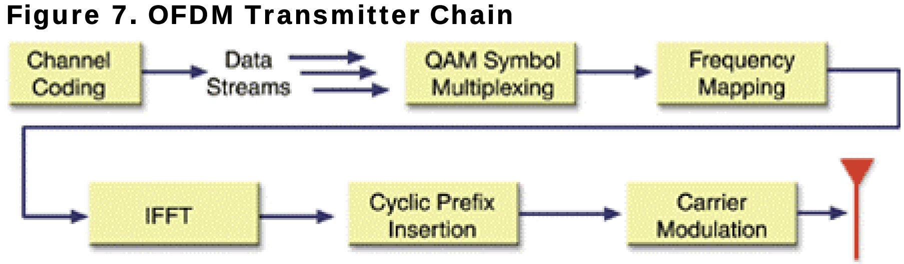
Figure 6. OFDM Tones



OFDM is a modulation technique in that it enables user data to be modulated onto the tones. The information is modulated onto a tone by adjusting the tone's phase, amplitude, or both. In the most basic form, a tone may be present or disabled to indicate a one or zero bit of information, however, either phase shift keying (PSK) or quadrature amplitude modulation (QAM) is typically employed. An OFDM system takes a data stream and splits it into N parallel data streams, each at a rate $1/N$ of the original rate. Each stream is then mapped to a tone at a unique frequency and combined together using the inverse fast fourier transform (IFFT) to yield the time-domain waveform to be transmitted.

For example, if a 100-tone system were used, a single data stream with a rate of 1 megabit per second (Mbps) would be converted into 100 streams of 10 kilobits per second (kbps). By creating slower parallel data streams, the bandwidth of the modulation symbol is effectively decreased by a factor of 100, or, equivalently, the duration of the modulation symbol is increased by a factor of 100. Proper selection of system parameters, such as the number of tones and tone spacing, can greatly reduce, or even eliminate, ISI, because typical multipath delay spread represents a much smaller proportion of the lengthened symbol time. Viewed another way, the coherence bandwidth of the channel can be much smaller, because the symbol bandwidth has been reduced. The need for complex multi-tap time-domain equalizers can be eliminated as a result.

Figure 7. OFDM Transmitter Chain

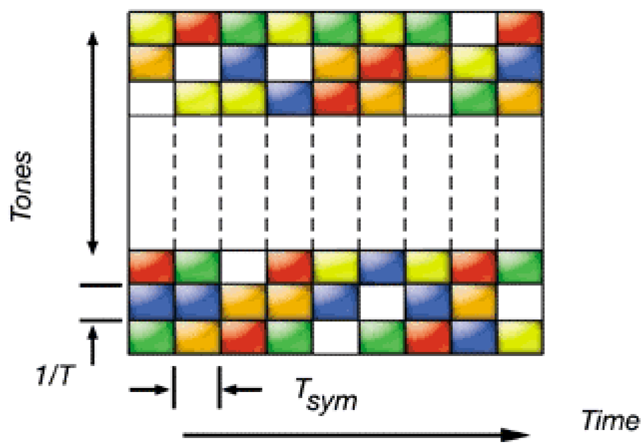


OFDM can also be considered a multiple-access technique, because an individual tone or groups of tones can be assigned to different users. Multiple users share a given bandwidth in this manner, yielding the system called OFDMA. Each user can be assigned a predetermined number of tones when they have information to send, or alternatively, a user can be assigned a variable number of tones based on the amount of information that they have to send. The assignments are controlled by the media access control (MAC) layer, which schedules the resource assignments based on user demand.

OFDM can be combined with frequency hopping to create a spread spectrum system, realizing the benefits of frequency diversity and interference averaging previously described for CDMA. In a frequency hopping spread spectrum system, each user's set of tones is changed after each time period (usually corresponding to a modulation symbol). By switching frequencies after each symbol time, the losses due to frequency selective fading are minimized. Although frequency hopping and CDMA are different forms of spread spectrum, they achieve comparable performance in a multipath fading environment and provide similar interference averaging benefits.

OFDM therefore provides the best of the benefits of TDMA in that users are orthogonal to one another, and CDMA, as previously mentioned, while avoiding the limitations of each, including the need for TDMA frequency planning and equalization, and multiple access interference in the case of CDMA.

Figure 8. Two-Dimensional Illustration of OFDM Channel Resource



Theory of OFDM Operation

The sinusoidal waveforms making up the tones in OFDM have the very special property of being the only Eigen-functions of a linear channel. This special property prevents adjacent tones in OFDM systems from interfering with one another, in much the same manner that the human ear can clearly distinguish between each of the tones created by the adjacent keys of a piano. This property, and the incorporation of a small amount of guard time to each symbol, enables the orthogonality between tones to be preserved in the presence of multipath. This is what enables OFDM to avoid the multiple-access interference that is present in CDMA systems.

The frequency domain representation of a number of tones, shown in *Figure 6*, highlights the orthogonal nature of the tones used in the OFDM system. Notice that the peak of each tone corresponds to a zero level, or null, of every other tone. The result of this is that there is no interference between tones. When the receiver samples at the center frequency of each tone, the only energy present is that of the desired signal, plus whatever other noise happens to be in the channel.

To maintain orthogonality between tones, it is necessary to ensure that the symbol time contains one or multiple cycles of each sinusoidal tone waveform. This is normally the case, because the system numerology is constructed such that tone frequencies are integer multiples of the symbol period, as is subsequently highlighted, where the tone spacing is 1/T. Viewed as sinusoids, *Figure 9* shows three tones over a single symbol period, where each tone has an integer number of cycles during the symbol.

Figure 9. Time- and Frequency-Domain Representation of OFDM

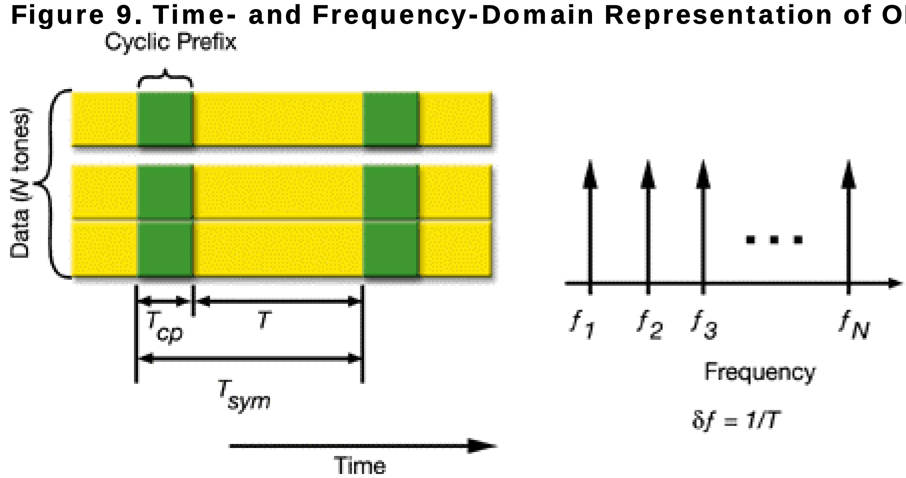
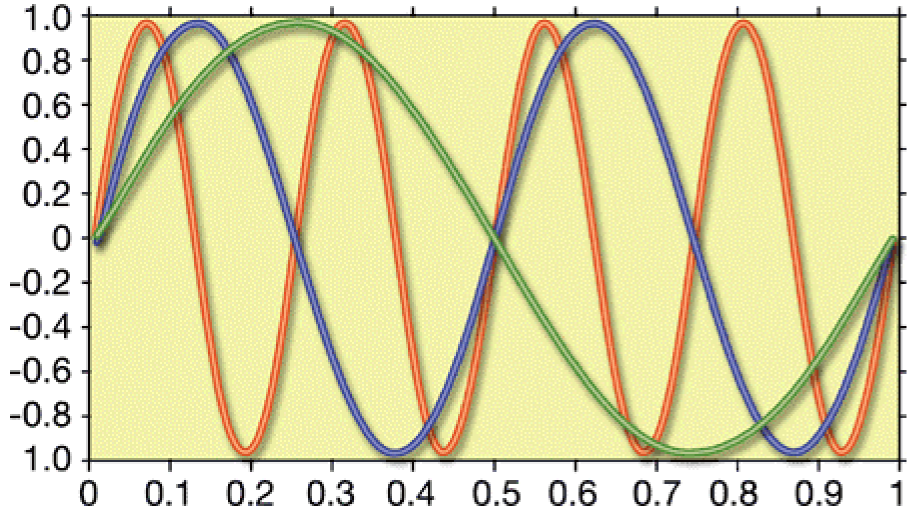


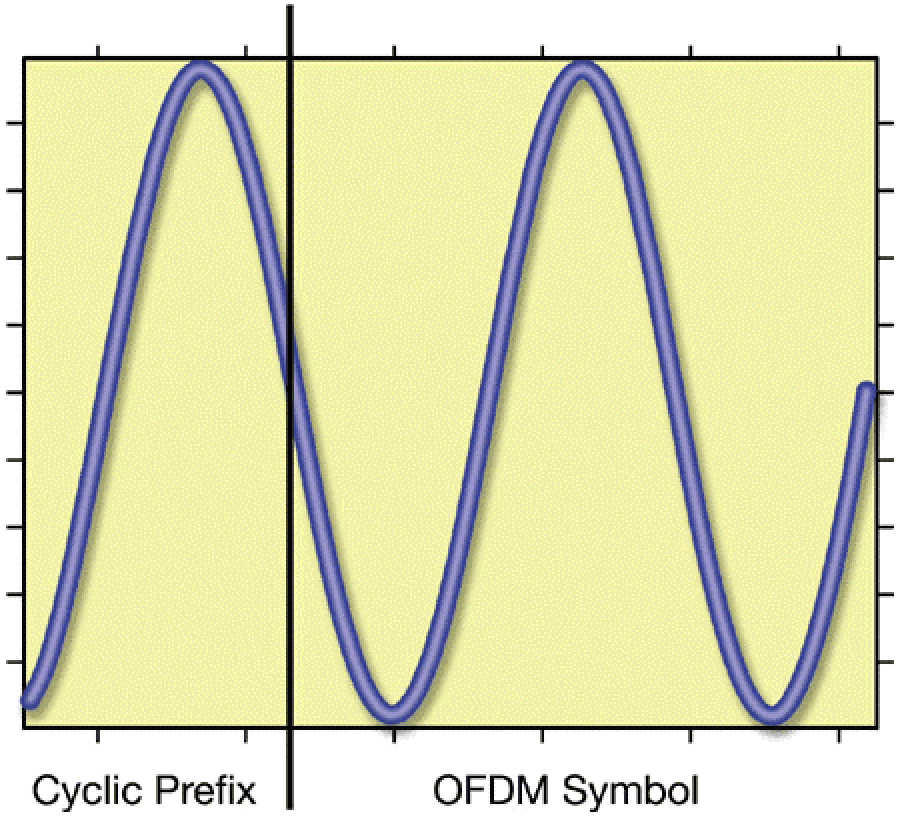
Figure 10. Integer Number of Sinusoid Periods



In absolute terms, to generate a pure sinusoidal tone requires the signal start at time minus infinity. This is important, because tones are the only waveform than can ensure orthogonality. Fortunately, the channel response can be treated as finite, because multipath components decay over time and the channel is effectively band-limited. By adding a guard time, called a cyclic prefix, the channel can be made to behave as if the transmitted waveforms were from time minus infinite, and thus ensure orthogonality, which essentially prevents one subcarrier from interfering with another (called intercarrier interference, or ICI).

The cyclic prefix is actually a copy of the last portion of the data symbol appended to the front of the symbol during the guard interval, as shown in *Figures 9* and *11*. Multipath causes tones and delayed replicas of tones to arrive at the receiver with some delay spread. This leads to misalignment between sinusoids, which need to be aligned as in *Figure 11* to be orthogonal. The cyclic prefix allows the tones to be realigned at the receiver, thus regaining orthogonality.

Figure 11. Cyclic Extension of Sinusoid



The cyclic prefix is sized appropriately to serve as a guard time to eliminate ISI. This is accomplished because the amount of time dispersion from the channel is smaller than the duration of the cyclic prefix. A fundamental trade-off is that the cyclic prefix must be long enough to account for the anticipated multipath delay spread experienced by the system. The amount of overhead increases, as the cyclic prefix gets longer. The sizing of the cyclic prefix forces a tradeoff between the amount of delay spread that is acceptable and the amount of Doppler shift that is acceptable.

5. Leading-Edge Mobile OFDM Technologies

Unlike most existing forms of wireless access, including 3G technologies, conventional wireless systems have been designed primarily at the physical layer. To address the unique demands posed by mobile users of high-speed data applications, new air interfaces must be designed and optimized across all the layers of the protocol stack, including the networking layers. A prime example of this kind of optimization is found in flash-OFDM™ technology by Flarion. As its name suggests, the system is based on OFDM, however, flash-OFDM is much more than just a physical-layer solution. It is a system-level technology that exploits the unique physical properties of OFDM, enabling significant higher-layer advantages that contribute to very efficient packet data transmission in a cellular network.

Packet Switched Air Interface

The telephone network, designed basically for voice, is an example of circuit-switched systems. Circuit-switched systems exist only at the physical layer that uses the channel resource to create a bit pipe. They are conceptually simple as the bit pipe is a dedicated resource, and there is no control of the pipe required once it is created (some control may be required in setting up or bringing down the pipe). Circuit-switched systems, however, are very inefficient for burst data traffic.

Packet-switched systems, on the other hand, are very efficient for data traffic but require control layers in addition to the physical layer that creates the bit pipe. The MAC layer is required for the many data users to share the bit pipe. The link layer is needed to take the error-prone pipe and create a reliable link for the network layers to pass packet data flows over. The Internet is the best example of a packet-switched network.

Because all conventional cellular wireless systems, including 3G, were fundamentally designed for circuit -witched voice, they were designed and optimized primarily at the physical layer. The choice of CDMA[1] as the physical-layer multiple-access technology was also dictated by voice requirements. Flash-OFDM, on the other hand, is a packet-switched designed for data and is optimized across the physical, MAC, link, and network layers. The choice of OFDM as the multiple-access technology is based not just on physical-layer consideration, but also on MAC–, link-, and network-layer requirements.

Physical-Layer Advantages

As discussed earlier, most of the physical-layer advantages of OFDM are well understood. Most notably, OFDM creates a robust multiple-access technology to deal with the impairments of the wireless channel, such as multipath fading, delay spread, and Doppler shifts. Advanced OFDM–based data systems typically divide the available spectrum into a number of equally spaced tones. For each OFDM symbol duration, information carrying symbols (based on modulation such as QPSK, QAM, etc.) are loaded on each tone.

Flash-OFDM uses fast hopping across all tones in a pseudorandom predetermined pattern, making it a spread spectrum technology. With fast hopping, a user that is assigned one tone does not transmit every symbol on the same tone, but uses a hopping pattern to jump to a different tone for every symbol. Different base stations use different hopping patterns, and each uses the entire available spectrum (frequency reuse of 1). In a cellular deployment, this leads to all the advantages of CDMA systems, including frequency diversity[2] and out of cell (intercell) interference averaging—a spectral-efficiency benefit that narrowband systems such as conventional TDMA do not have.

As discussed earlier, different users within the same cell use different resources (tones) and hence do not interfere with each other. This is similar to TDMA, where different users in a cell transmit at different time slots and do not interfere with one another. In contrast, CDMA users in a cell do interfere with each other, increasing the total interference in the system. Flash-OFDM therefore has the physical-layer benefits of both CDMA and TDMA and is at least three times more efficient than CDMA. In other words, at the physical layer, flash-OFDM creates the fattest pipe of all cellular technologies. Even though the 3x advantage at the physical layer is a huge advantage, the most significant advantage of flash-OFDM for data is at the MAC and link layers.

MAC and Link-Layer Advantages

Flash-OFDM exploits the granular nature of resources in OFDM to come up with extremely efficient control layers. In OFDM, when designed appropriately, it is possible to send a very small amount (as little as one bit) of information from the transmitter to the receiver with virtually no overhead. Therefore, a transmitter that is previously not transmitting can start transmitting, transmit as little as one bit of information, and then stop, without causing any resource overhead. This is unlike CDMA or TDMA, in which the granularity is much coarser and to merely initiate a transmission wastes a significant resource. Hence, in TDMA, for example, there is a frame structure, and whenever a transmission is initiated, a minimum of one frame (a few hundred bits) of information is transmitted. The frame structure does not cause any significant inefficiency in user data transmission, as data traffic typically consists of a large number of bits. However, for transmission of control-layer information, the frame structure is extremely inefficient, as the control information typically consists of one or two bits but requires a whole frame. Not having a granular technology can therefore be very detrimental from a MAC– and link-layer point of view.

Flash-OFDM takes advantage of the granularity of OFDM in its control-layer design, enabling the MAC layer to perform efficient packet switching over the air and at the same time providing all the hooks to handle QoS. It also supports a link layer that uses local (as opposed to end-to-end) feedback to create a very reliable link from an unreliable wireless channel, with very low delays. The network layer's traffic therefore experiences small delays and no significant delay jitter. Hence, interactive applications such as (packet) voice can be supported. Moreover, Internet protocols such as TCP/IP run smoothly and efficiently over a flash-OFDM airlink. TCP/IP performance on 3G networks is very inefficient because the link layer introduces significant delay jitter so that channel errors are misinterpreted by TCP as network congestion and TCP responds by backing off to the lowest rate.

Packet switching leads to efficient statistical multiplexing of data users and helps the wireless operators to support a much higher number of users for a given user experience. This, together with QoS support and a 3x fatter pipe, allows the operators to profitably scale their wireless networks to meet the burgeoning data-traffic demand in an all-you-can-eat pricing environment.

1 3G system in Europe (WCDMA) and the United States (CDMA 2000) are based on CDMA technology.

3 Frequency diversity provides immunity in a fading environment, where a users' signal spans a wide spectrum and usually does not fade at the same time.

6. Conclusion

This tutorial highlights the unique design challenges faced by mobile data systems that result from the vagaries of the harsh wireless channel, the wide and varied service profiles that are enabled by data communications, and the performance of wireline-based protocols, such as TCP/IP, with the realities of wireless links. OFDM has been shown to address these challenges and to be a key enabler of a system design that can provide high-performance mobile data communications.

OFDM is well positioned to meet the unique demands of mobile packet data traffic. Nevertheless, to seamlessly unwire all the IP applications inherent in the wired Internet and intranets (including interactive data applications and peer-to-peer applications), all layers of the OFDM air interface need to be jointly designed and optimized from the ground up for the IP data world. This means to not rely solely on OFDM's physical layer advantages, but rather to leverage them into all of the higher layers of the system.

Self-Test

1. What makes the wireless channel more unpredictable than the wireline channel?

    a. Multipath

    b. Doppler spread

    c. Shadow fading

    d. All of the above

2. Rayleigh fading occurs when there is:

a. A LOS component present

b. No LOS component present

c. Intercell interference

d. None of the above

3. Spread spectrum systems employ a form of diversity called __________, where the signal is spread over a much larger bandwidth than is needed.

   a. Frequency diversity

   b. Spatial diversity

   c. Bandwidth diversity

   d. Radio diversity

4. The use of equalizers adds to the complexity and costs of the ______ systems, because equalization requires significant amounts of signal-processing power.

   a. CDMA

   b. TDMA

   c. OFDM

   d. FDMA

5. With ______, fast and accurate power-control loops must be used so that the signal from one user does not drown out the signals from other users, and each cell must be tightly synchronized. Errors in power control and time synchronization will result in reduced capacity and system performance.

   a. CDMA

   b. TDMA

   c. OFDM

   d. FDMA

6. Both OFDM and CDMA systems have code sequences that are truly orthogonal in the presence of multipath delay spread.

   a. True

b. False

7. Whereas TDMA segments are according to time and CDMA segments are according to spreading codes, OFDM segments are according to frequency.

    a. True

    b. False

8. OFDM therefore provides the best of the benefits of TDMA (in that users are orthogonal to one another) and CDMA, thus enabling frequency diversity and out-of-cell interference.

    a. True

    b. False

9. Time dispersion leads to intersymbol interference, or ISI, where the energy from one symbol spills over into another symbol, decreasing the BER as a result.

    a. True

    b. False

10. OFDM allows the spectrum of each tone to overlap, and because they are orthogonal, they do not interfere with each other. By allowing the tones to overlap, the overall amount of spectrum required is reduced.

    a. True

    b. False

Correct Answers

1. What makes the wireless channel more unpredictable than the wireline channel?

    a. Multipath

    b. Doppler spread

    c. Shadow fading

    d. All of the above

See Topic 2

2. Rayleigh fading occurs when there is:

a. A LOS component present

b. No LOS component present

c. Intercell interference

d. None of the above

See Topic 3

3. Spread spectrum systems employ a form of diversity called _________, where the signal is spread over a much larger bandwidth than is needed.

a. Frequency diversity

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See Topic 3

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See Topic 4

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See Topic 4

Glossary

3G
Third-Generation

ARQ
Automatic Retransmission Request

BER
Bit-Error Rate

CDMA
Code Division Multiple Access

dB
Decibel

DSL
Digital Subscriber Line

FDM
Frequency Division Multiplexing

FEC
Forward Error Correction

FH
Frequency Hopping

ICI
Intercarrier Interference

IFFT
Inverse Fast Fourier Transform

IP
Internet Protocol

ISI
Intersymbol Interference

LOS
Line of Sight

MAC
Media Access Control

OFDM
Orthogonal Frequency Division Multiplexing

PCS
Personal Communications Service

PSK
Phase Shift Keying

QAM
Quadrature Amplitude Modulation

QoS
Quality of Service

RF
Radio Frequency

SLA
Service-Level Agreement

TCP
Transport Control Protocol

TDMA
Time Division Multiple Access

VoIP
Voice over Internet Protocol

WCDMA
Wideband Code Division Multiple Access