Orthogonal frequency division multiplexing (OFDM)

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Abstract

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). 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.

Inroduction

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.

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 1. OFDM Tones

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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 2. OFDM Transmitter Chain

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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 3. Two-Dimensional Illustration of OFDM Channel Resource

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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 4* shows three tones over a single symbol period, where each tone has an integer number of cycles during the symbol.

Figure 4. Time- and Frequency-Domain Representation of OFDM

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Figure 5. Integer Number of Sinusoid Periods

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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 4* and 6. 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 6. Cyclic Extension of Sinusoid

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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.

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[11] 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.

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

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[22] 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

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[2] 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.

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.

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.

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