The principles of OFDM

Multicarrier modulation techniques are rapidly moving from the textbook to the real world of modern communication systems

By Louis Litwin and Michael Pugel

The principles of orthogonal frequency division multiplexing (OFDM) modulation have been in existence for several decades. However, in recent years these techniques have quickly moved out of textbooks and research laboratories and into practice in modern communications systems. The techniques are employed in data delivery systems over the phone line, digital radio and television, and wireless networking systems. What is OFDM? And why has it recently become so popular? This article will review the fundamentals behind OFDM tech-
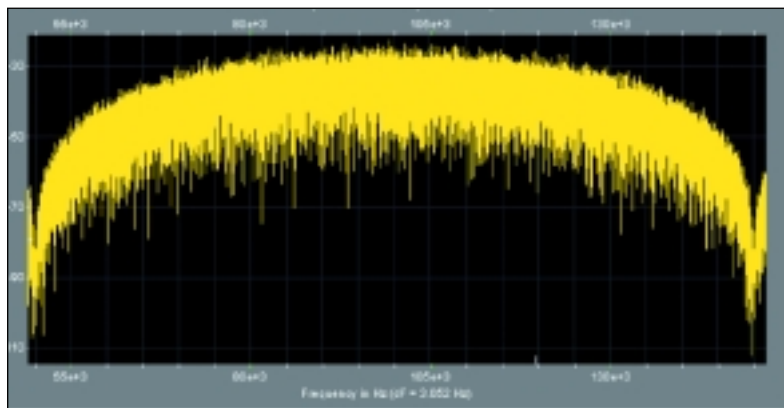

Figure 1. Single carrier spectrum example.

niques, and also discuss common impairments and how, in some cases, OFDM mitigates their effect. Where applicable, the impairment effects and techniques will be compared to those in a single carrier system. A brief overview of some modern applications will conclude the article.

The single-carrier modulation system

A typical single-carrier modulation spectrum is shown in Figure 1. A single carrier system modulates information onto one carrier using frequency, phase, or amplitude adjustment of the carrier. For

digital signals, the information is in the form of bits, or collections of bits called symbols, that are modulated onto the carrier. As higher bandwidths (data rates) are used, the duration of one bit or symbol of information becomes smaller. The system becomes more susceptible to loss of information from impulse noise, signal reflections and other impairments. These impairments can impede the ability to recover the information sent. In addition, as the bandwidth used by a single carrier system increases, the susceptibility to interference from other continuous signal sources becomes greater. This type of interference is commonly labeled as carrier wave (CW) or frequency interference.

Frequency division multiplexing modulation system

Frequency division multiplexing (FDM) extends the concept of single carrier modulation by using multiple subcarriers within the same single channel. The total data rate to be sent in the channel is divided between the various subcarriers. The data do not have to be divided evenly nor do they have to originate from the same information source. Advantages include using separate modulation/demodulation customized to a particular type of data, or sending out banks of dissimilar data that can be best sent using multiple, and possibly different, modulation schemes.

Current national television systems committee (NTSC) television and FM stereo multiplex are good examples of FDM. FDM offers an advantage over single-carrier modulation in terms of narrowband frequency interference since this interference will only affect one of the frequency subbands. The other subcarriers will not be affected by the interference. Since each subcarrier has a lower information rate, the data symbol periods in a digital system will be longer, adding some additional immunity to impulse noise and reflections.

FDM systems usually require a guard band between modulated subcarriers to prevent the spectrum of one subcarrier from interfering with another. These guard bands lower the system's effective information rate when compared to a single carrier system with similar modulation.

Orthogonality and OFDM

If the FDM system above had been able to use a set of subcarriers that were orthogonal to each other, a higher level of spectral efficiency could have been achieved. The guardbands that were necessary to allow individual demodulation of subcarriers in an FDM system would no longer be necessary. The use of orthogonal subcarriers would allow the subcarriers' spectra to overlap, thus increasing the spectral efficiency. As long as orthogonality is maintained, it is still possible to recover the individual subcarriers' signals despite their overlapping spectrums.

If the dot product of two deterministic signals is equal to zero, these signals are said to be orthogonal to each other. Orthogonality can also be
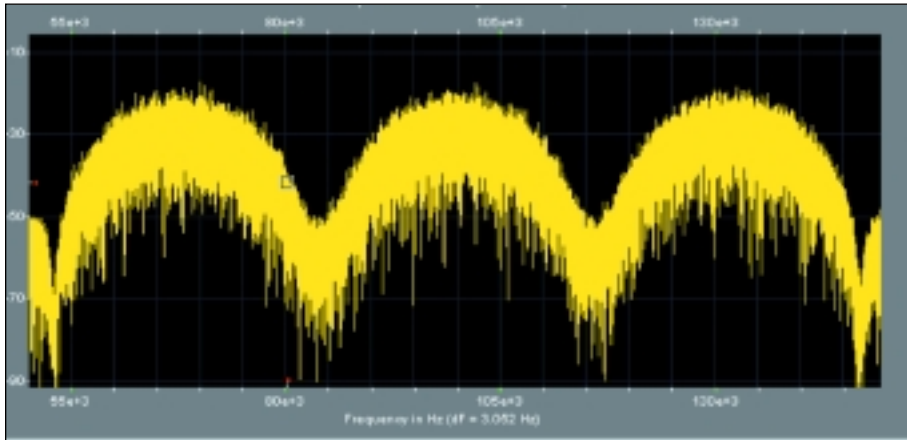
Figure 2. FDM signal spectrum example.

viewed from the standpoint of stochastic processes. If two random processes are uncorrelated, then they are orthogonal. Given the random nature of signals in a communications system, this probabilistic view of orthogonality provides an intuitive understanding of the implications of orthogonality in OFDM. Later in this article, we will discuss how OFDM is implemented in practice using the discrete fourier transform (DFT). Recall from signals and systems theory that the sinusoids of the DFT form an orthogonal basis set, and a signal in the vector space of the DFT can be represented as a linear combination of the orthogonal sinusoids. One view of the DFT is that the transform essentially correlates its input signal with each of the sinusoidal basis functions. If the input signal has some energy at a cer-

tain frequency, there will be a peak in the correlation of the input signal and the basis sinusoid that is at that corresponding frequency. This transform is used at the OFDM transmitter to map an input signal onto a set of orthogonal subcarriers, i.e., the orthogonal basis functions of the DFT. Similarly, the transform is used again at the OFDM receiver to process the received subcarriers. The signals from the subcarriers are then combined to form an estimate of the source signal from the transmitter. The orthogonal and uncorrelated nature of the subcarriers is exploited in OFDM with powerful results. Since the basis functions of the DFT are uncorrelated, the correlation performed in the DFT for a given subcarrier only sees energy for that corresponding subcarrier. The energy from other subcarriers does not contribute because it is uncorrelated. This separation of signal energy is the rea-

son that the OFDM subcarriers' spectrums can overlap without causing interference.

A simple OFDM example

Figure 3 shows a simple representation of an OFDM system. These types of systems have been built but the practicality of such construction quickly diminishes as the number of subcarriers increases. Each subcarrier carries one bit of information (N bits total) by its presence or absence in the output spectrum. The frequency of each subcarrier is selected to form an orthogonal signal set, and these frequencies are known at the receiver. Note that the output is updated at a periodic interval T that forms the symbol period as well as the time boundary for orthogonality. Figure 4 shows the resultant frequency spectrum. In the frequency domain, the resulting sin function side lobes produce overlapping spectra. The individual peaks of subbands all line up with the zero crossings of the other subbands. This overlap of spectral energy does not interfere with the system's ability to recover the original signal. The receiver multiplies (i.e., correlates) the incoming signal by the known set of sinusoids to produce the original set of bits sent. The digital implementation of an OFDM system will enhance these simple principles and permit more complex modulation.

Implementation of an OFDM system

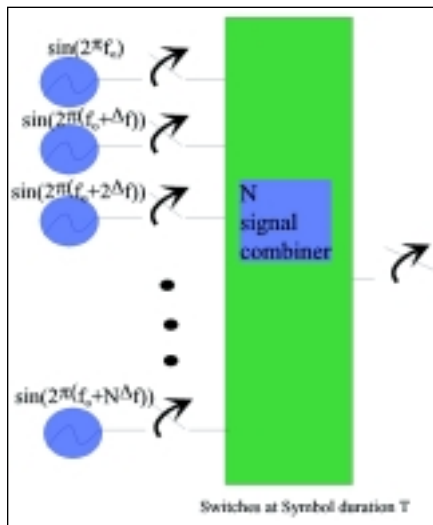The idea behind the analog implementation of OFDM can be extended to

Figure 3. A Simple OFDM generator. N subcarriers transmitting 1 bit of information each, by turning on and off at time intervals T.
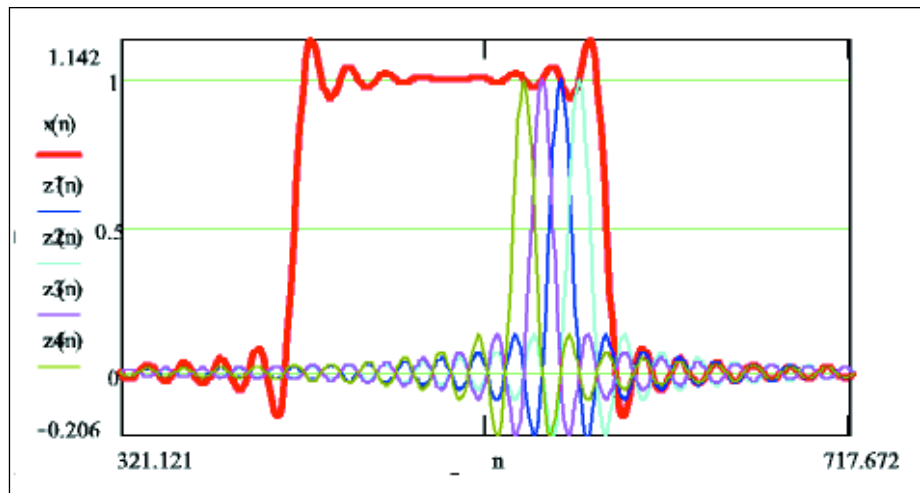

Figure 4. Overall spectrum of the simple OFDM signal shown with four subcarriers within. Note that the zero crossings all correspond to peaks of adjacent subcarriers.
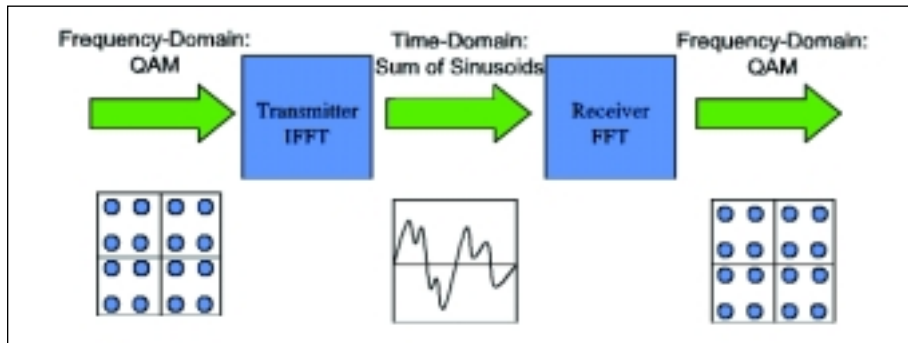
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Figure 5. Block diagram of a simple OFDM system.

the digital domain by using the discrete Fourier Transform (DFT) and its counterpart, the inverse discrete Fourier Transform (IDFT). These mathematical operations are widely used for transforming data between the time-domain and frequency-domain. These transforms are interesting from the OFDM perspective because they can be viewed as mapping data onto orthogonal subcarriers. For example, the IDFT is used to take in frequency-domain data and convert it to time-domain data. In order to perform that operation, the IDFT correlates the frequency-domain input data with its orthogonal basis functions, which are sinusoids at certain frequencies. This correlation is equivalent to mapping the input data onto the sinusoidal basis functions.

In practice, OFDM systems are implemented using a combination of fast Fourier Transform (FFT) and inverse fast Fourier Transform (IFFT) blocks that are mathematically equivalent versions of the DFT and IDFT, respectively, but more efficient to implement. An OFDM system treats the source symbols (e.g., the QPSK or QAM symbols that would be present in a single carrier system) at the transmitter as though they are in the frequency-domain. These symbols are used as the inputs to an IFFT block that brings the signal into the time-domain. The IFFT takes in N symbols at a time where N is the number of subcarriers in the system. Each of these N input symbols has a symbol period of T seconds. Recall that the basis functions for an IFFT are N orthogonal sinusoids. These sinusoids each have a different frequency and the lowest frequency is DC. Each input symbol acts like a complex weight for the corresponding sinusoidal basis function. Since the input symbols are complex, the value of the symbol determines both the ampli-

tude and phase of the sinusoid for that subcarrier. The IFFT output is the summation of all N sinusoids. Thus, the IFFT block provides a simple way to modulate data onto N orthogonal subcarriers. The block of N output samples from the IFFT make up a single OFDM symbol. The length of the OFDM symbol is NT where T is the IFFT input symbol period mentioned above.

After some additional processing, the time-domain signal that results from the IFFT is transmitted across the channel. At the receiver, an FFT block is used to process the received signal and bring it into the frequency-domain. Ideally, the FFT output will be the original symbols that were sent to the IFFT at the transmitter. When plotted in the complex plane, the FFT output samples will form a constellation, such as 16-QAM. However, there is no notion of a constellation for the time-domain signal. When plotted on the complex plane, the time-domain signal forms a scatter plot with no regular shape. Thus, any receiver processing that uses the concept of a constellation (such as symbol slicing) must occur in the frequency-domain. The block diagram in Figure 5 illustrates the switch between frequency-domain and time-domain in an OFDM system.
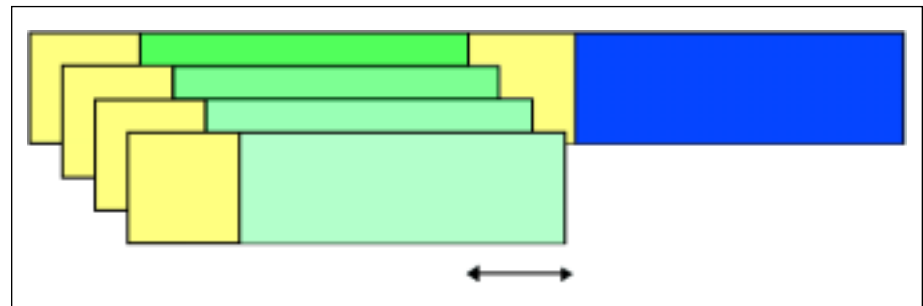
Multipath channels and the use of cyclic prefix

A major problem in most wireless systems is the presence of a multipath channel. In a multipath environment, the transmitted signal reflects off of several objects. As a result, multiple delayed versions of the transmitted signal arrive at the receiver. The multiple versions of the signal cause the received signal to be distorted. Many wired systems also have a similar problem where reflections occur due to impedance mismatches in the transmission line.

A multipath channel will cause two problems for an OFDM system. The first problem is intersymbol interference. This problem occurs when the received OFDM symbol is distorted by the previously transmitted OFDM symbol. The effect is similar to the intersymbol interference that occurs in a single-carrier system. However, in such systems, the interference is typically due to several other symbols instead of just the previous symbol; the symbol period in single carrier systems is typically much shorter than the time span of the channel, whereas the typical OFDM symbol period is much longer than the time span of the channel. The second problem is unique to multicarrier systems and is called Intrasymbol Interference. It is the result of interference amongst a given OFDM symbol's own subcarriers. The next sections illustrate how OFDM deals with these two types of interference.

Intersymbol interference

Assume that the time span of the channel is L_C samples long. Instead of a single carrier with a data rate of R symbols/second, an OFDM system has N subcarriers, each with a data rate of R/N symbols/second. Because the data rate is reduced by a factor of N, the OFDM symbol period is increased by a factor of N. By choosing an appropriate

Figure 6. Example of intersymbol interference. The green symbol was transmitted first, followed by the blue symbol.
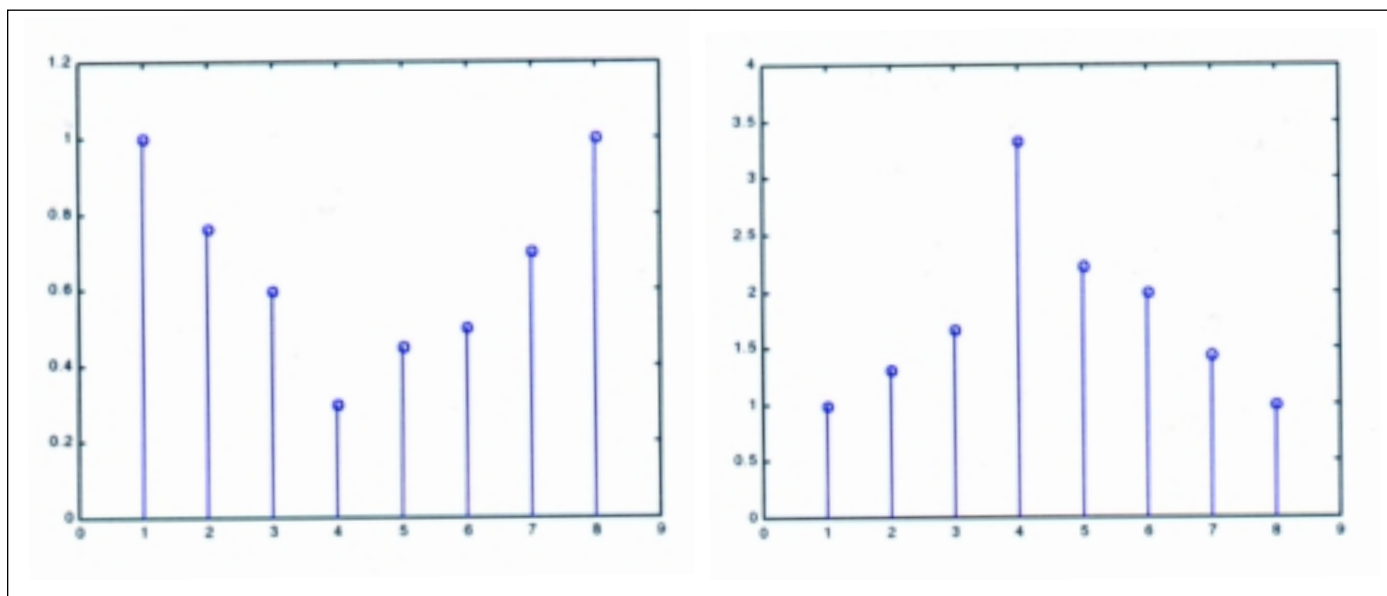
Figure 7. Left plot shows the frequency response of a channel, and the right plot shows the corresponding frequency-domain equalizer response. Note that the equalizer response is large when the channel response is small in order to counteract the effect of a channel null.

value for N, the length of the OFDM symbol becomes longer than the time span of the channel. Because of this configuration, the effect of intersymbol interference is the distortion of the first L_C samples of the received OFDM symbol. An example of this effect is shown in Figure 6. By noting that only the first few samples of the symbol are distorted, one can consider the use of a guard interval to remove the effect of inter-symbol interference. The guard interval could be a section of all zero samples transmitted in front of each OFDM symbol. Since it does not contain any useful information, the guard interval would be discarded at the receiver. If the length of the guard interval is properly chosen such that it is longer than the time span of the channel, the OFDM symbol itself will not be distorted. Thus, by discarding the guard interval, the effects of intersymbol interference are thrown away as well.

Intrasymbol interference

The guard interval is not used in practical systems because it does not prevent an OFDM symbol from interfering with itself. This type of interference is called intrasymbol interference. The solution to the problem of intrasymbol interference involves a discrete-time property. Recall that in continuous-time, a convolution in time is equivalent to a multiplication in the frequency-domain. This property is true in discrete-time only if the signals

are of infinite length or if at least one of the signals is periodic over the range of the convolution. It is not practical to have an infinite-length OFDM symbol, however, it is possible to make the OFDM symbol appear periodic. This periodic form is achieved by replacing the guard interval with something known as a cyclic prefix of length L_P samples. The cyclic prefix is a replica of the last L_P samples of the OFDM symbol where $L_P > L_C$. Since it contains redundant information, the cyclic prefix is discarded at the receiver. Like the case of the guard interval, this step removes the effects of inter-symbol interference. Because of the way in which the cyclic prefix was formed, the cyclically-extended OFDM symbol now appears periodic when convolved with the channel. An important result is that the effect of the channel becomes multiplicative.

In a digital communications system, the symbols that arrive at the receiver have been convolved with the time-domain channel impulse response of length L_C samples. Thus, the effect of the channel is convolutional. In order to undo the effects of the channel, another convolution must be performed at the receiver using a time-domain filter known as an equalizer. The length of the equalizer needs to be on the order of the time span of the channel. The equalizer processes symbols in order to adapt its response in an attempt to remove the effects of the

channel. Such an equalizer can be expensive to implement in hardware and often requires a large number of symbols in order to adapt its response to a good setting.

In OFDM, the time-domain signal is still convolved with the channel response. However, the data will ultimately be transformed back into the frequency-domain by the FFT in the receiver. Because of the periodic nature of the cyclically-extended OFDM symbol, this time-domain convolution will result in the multiplication of the spectrum of the OFDM signal (i.e., the frequency-domain constellation points) with the frequency response of the channel. The result is that each subcarrier's symbol will be multiplied by a complex number equal to the channel's frequency response at that subcarrier's frequency. Each received subcarrier experiences a complex gain (amplitude and phase distortion) due to the channel. In order to undo these effects, a frequency-domain equalizer is employed. Such an equalizer is much simpler than a time-domain equalizer. The frequency-domain equalizer consists of a single complex multiplication for each subcarrier. For the simple case of no noise, the ideal value of the equalizer's response is the inverse of the channel's frequency response. An example is shown in Figure 7. With such a setting, the frequency-domain equalizer would cancel out the multiplicative effect of the channel.
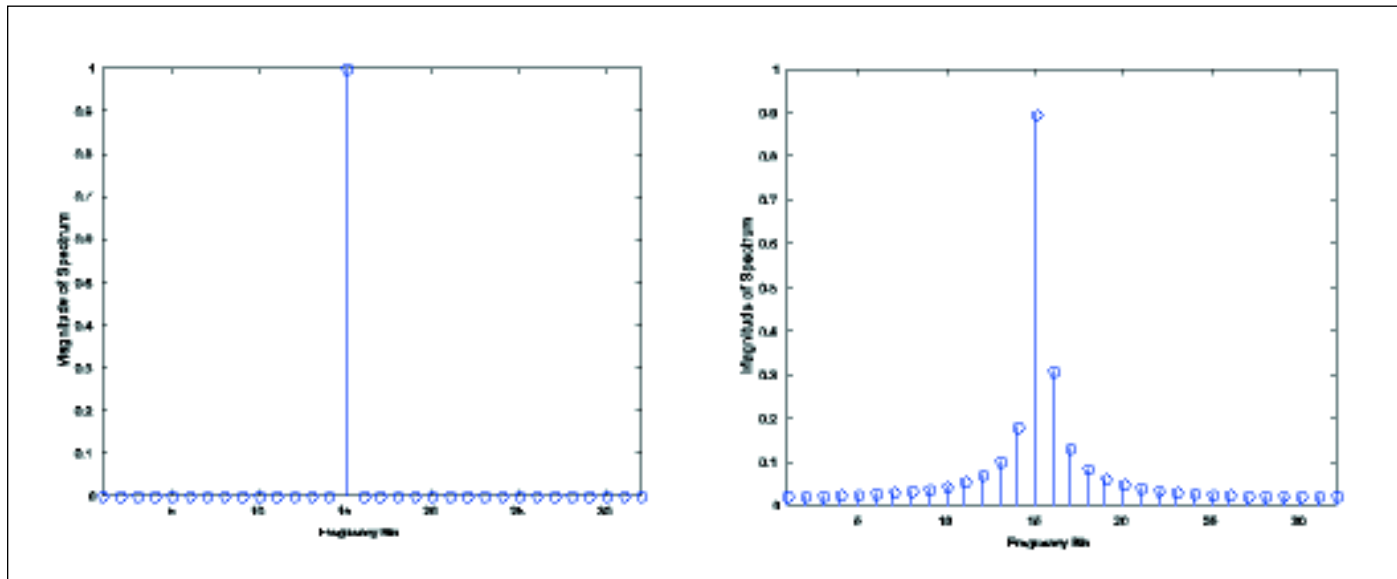
Figure 8. Received spectrum with one non-zero subcarrier. The left plot is for the case of no LO offset, and the right plot is for the presence of an LO offset.

COFDM: Coded OFDM

Coded OFDM, or COFDM, is a term used for a system in which the error control coding and OFDM modulation processes work closely together. An important step in a COFDM system is to interleave and code the bits prior to the IFFT. This step serves the purpose of taking adjacent bits in the source data and spreading them out across multiple subcarriers. One or more subcarriers may be lost or impaired due to a frequency null, and this loss would cause a contiguous stream of bit errors. Such a burst of errors would typically be hard to correct. The interleaving at the transmitter spreads out the contiguous bits such that the bit errors become spaced far apart in time. This spacing makes it easier for the decoder to correct the errors. Another important step in a COFDM system is to use channel information from the equalizer to determine the reliability of the received bits. The values of the equalizer response are used to infer the strength of the received subcarriers. For example, if the equalizer response had a large value at a certain frequency, it would correspond to a frequency null at that point in the channel. The equalizer response would have a large value at that point because it is trying to compensate for the weak received signal. This reliability information is passed on to the decoding blocks so that they can properly weight the bits when making decoding decisions. In the case of a frequency null, the bits would be marked as "low confidence"

and those bits would not be weighted as heavily as bits from a strong subcarrier. COFDM systems are able to achieve excellent performance on frequency-selective channels because of the combined benefits of multicarrier modulation and coding.

Non-ideal effects in an OFDM system

This section will examine the effects of non-idealities in an OFDM system. These effects will include impairments and receiver offsets. Because the fourier transform is a fundamental operation in OFDM, the effects of several offsets can be intuitively understood by applying fourier transform theory.

Local oscillator frequency offset

At start-up, the local oscillator (LO) frequency at the receiver is typically different from the LO frequency at the transmitter. A carrier tracking loop is used to adjust the receiver's LO frequency in order to match the transmitter's LO frequency as closely as possible. The effect of having an LO frequency offset can be explained by Fourier Transform theory. The LO offset can be expressed mathematically by multiplying the received time-domain signal by a complex exponential whose frequency is equal to the LO offset amount. Recall from Fourier Transform theory that multiplication by a complex exponential in time is equivalent to a shift in frequency. The LO offset results in a fre-

quency shift of the received signal spectrum. This shift causes a condition called "loss of orthogonality" to occur. The frequency shift causes the OFDM subcarriers to no longer be orthogonal. The orthogonality of the subcarriers is lost because the bins of the FFT will no longer line up with the peaks of the received signal's since pulses. The result is a distortion called inter-bin interference or IBI. IBI occurs when energy from one bin spills over into adjacent bins and this energy distorts the affected subcarriers. In Fourier Transform theory this effect is called DFT leakage.

The left plot of Figure 8 shows the spectrum of a received OFDM signal with no LO offset. For the purpose of clarity, only one non-zero subcarrier was transmitted. Note that this subcarrier is not interfering with its adjacent subcarriers. The spectrum of the non-zero subcarrier actually extends over the entire range of the FFT, however, due to the orthogonal nature of the signal, the zero-crossings of the spectrum exactly line up with the other FFT bins. The right plot of Figure 8 shows the received spectrum of the same signal with one non-zero subcarrier, however, in this case there is an LO offset. This offset has resulted in a loss of orthogonality, and the zero-crossings of the non-zero subcarrier's spectrum no longer line up with the FFT bins. The result is that energy from the non-zero subcarrier is spread out among all of the other subcarriers, with those sub-

carriers closest to the non-zero subcarrier receiving the most interference. This simple example was for the case of only one non-zero subcarrier. In a practical system, almost all of the subcarriers would be actively used for transmitting data. A given subcarrier would experience IBI due to energy from all of the other active subcarriers in the system. The central limit theorem states that the sum of a large number of random processes will result in a signal that has a Gaussian distribution. Because of this property, the IBI will manifest itself as additive Gaussian noise, thus lowering the effective SNR of the system.

The effect of an LO frequency offset can be corrected by multiplying the signal by a correction factor. The correction factor would be a sinusoid with a frequency that is ideally equal to the amount of the LO frequency offset. Various carrier tracking algorithms exist that can adaptively determine the frequency that will correct for the offset.

LO phase offset

It is also possible to have an LO phase offset, separate from an LO frequency offset. The two offsets can occur in conjunction or one or the other can be present by itself. As the name suggests, an LO phase offset occurs when there is a difference between the phase of the LO output and the phase of the received signal. This effect can be represented mathematically by multiplying the time-domain signal by a complex exponential with a constant phase. The result is a constant phase rotation for all of the subcarriers in the frequency-domain. The constellation points for each subcarrier experience the same degree of rotation. If the phase rotation

is small, the frequency-domain equalizer can correct this effect. Each filter coefficient in a frequency-domain equalizer multiplies its corresponding subcarrier by a complex gain (i.e., amplitude scaling and phase rotation). The equalizer's coefficients can be used to correct for a small phase rotation as long as the rotation doesn't cause the constellation points to rotate beyond the symbol decision regions. Larger phase rotations are corrected by a carrier tracking loop.

FFT window location offset

Another non-ideal effect that can occur in a real-world OFDM system is an FFT window location offset. An N-point FFT at the receiver processes data in blocks of N samples at a time. Ideally, the N samples taken in by the FFT will correspond to the N samples of a single transmitted OFDM symbol. In practice, a correlation is often used with a known preamble sequence located at the beginning of the transmission. This correlation operation aids the receiver in synchronizing itself with the received signal's OFDM symbol boundaries. However, inaccuracies still remain, and they manifest themselves as an offset in the FFT window location. The result is that the N samples sent to the FFT will not line up exactly with the corresponding OFDM symbol. If the offset is very large, part of the N samples will be from one OFDM symbol, and the rest of samples will be from another OFDM symbol. Such a situation would result in a severe distortion of the received subcarrier's constellations. Fortunately, such a large offset does not typically occur if a robust synchronization algorithm is used. More likely, an FFT window location offset of just a few samples will

occur. The presence of the cyclic prefix gives enough headroom to enable a small offset to be present without taking samples from more than one OFDM symbol. However, even an offset of just one sample will cause some degree of distortion. Again, the effect can be understood from Fourier Transform theory. The offset can be viewed as a shift in time. As long as the FFT window location offset does not go beyond an OFDM symbol boundary, this shift in time is equivalent to a linearly-increasing phase rotation in the frequency-domain constellations. Constellations on subcarriers corresponding to low frequencies will be rotated slightly, whereas constellations on higher-frequency subcarriers will experience a larger rotation. The amount of rotation increases linearly as the subcarrier's FFT bin location increases. Examples of the effects of different degrees of FFT window location offsets are shown in Figure 9.

FFT window location offsets are often corrected by performing a time-domain correlation with a known training sequence embedded in the transmitted signal. The location of the peak of the correlation allows the receiver to synchronize itself with the incoming signal.

Sampling frequency offset

Another potentially harmful situation is the presence of a sampling frequency offset. This condition occurs when the A/D converter output is sampled either too fast or too slow. Recall that $F_S/2$ is the highest available frequency in discrete-time where F_S is the sampling frequency. Sampling too fast essentially increases the value of $F_S/2$ and the result is a contracted (i.e.,
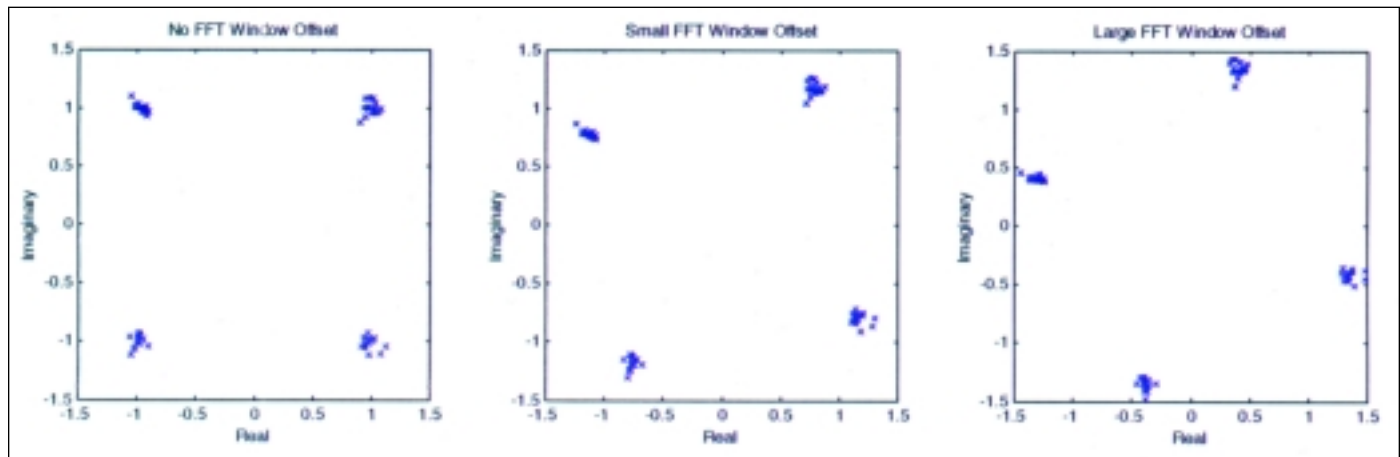

Figure 9. Effect of different FFT window offsets.

squashed) spectrum. Similarly, sampling too slow decreases the value of $F_S/2$ and results in an expanded spec-

Figure 10. Illustration of the effect of a sampling frequency offset.

trum. If the spectrum expands too much, aliasing of the spectrum can occur. Either type of sampling frequency offset results in IBI since the expansion or contraction of the spectrum prevents the received subcarriers from lining up with the FFT bin locations. The effect of sampling too fast is illustrated in Figure 10 and simulation results to demonstrate this effect are shown in Figure 11. A sampling frequency offset can be corrected by generating an error term that is used to drive a sampling rate converter.

Uniform noise

Additive white Gaussian noise (AWGN) is the most common impairment encountered in a communications

Figure 11. Simulation results showing the effect of a sampling frequency that is too high. Note that the sample that was originally at bin 15 is now at bin 8.

system. In a wireless medium, the noise source is typically considered to be thermal noise that is Gaussian and uniform across the frequency range. Additional noise sources include atmospheric sources and solar radiation. In a contained media, such as a coaxial cable system, thermal noise will be present,

but the system may also have other sources that can increase the noise in the system. The effect of AWGN on an OFDM system is similar to its effect on a single carrier system. The signal-to-noise ratio (SNR) is a function of the total signal power over the total noise power across the received channel. The uniform noise contributes to the SNR of each subcarrier in the OFDM system and the net result is equivalent to the effect on single channel systems.

Non-uniform noise

Noise in a communications channel can often be shaped, or "colored", by various effects. These effects can include transmit signal imperfections, transmission channel characteristics, or receiver frequency shaping. The implications of these effects for an OFDM system can be different compared to its single-carrier counterpart. The modulation of the OFDM system can be tailored for the noise characteristics. One method previously mentioned involves lowering the modulation (number of bits/symbol) on subcarriers in a low SNR environment as illustrated in Figure 12. Another method involves

sending the same data on several subcarriers, or sending data that can be considered lower priority. In extreme cases, the subcarriers can transmit no data, essentially turning them off.
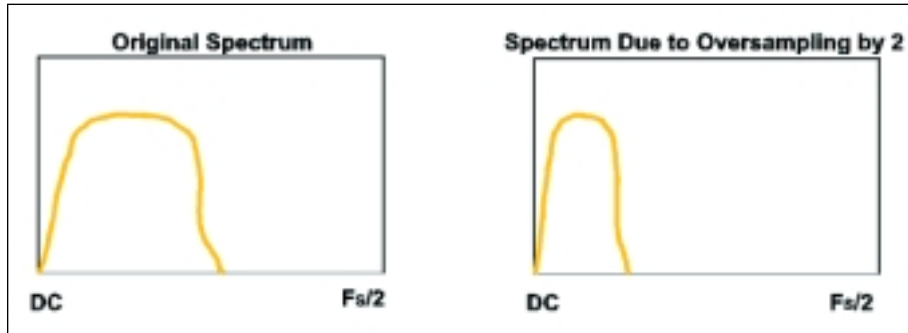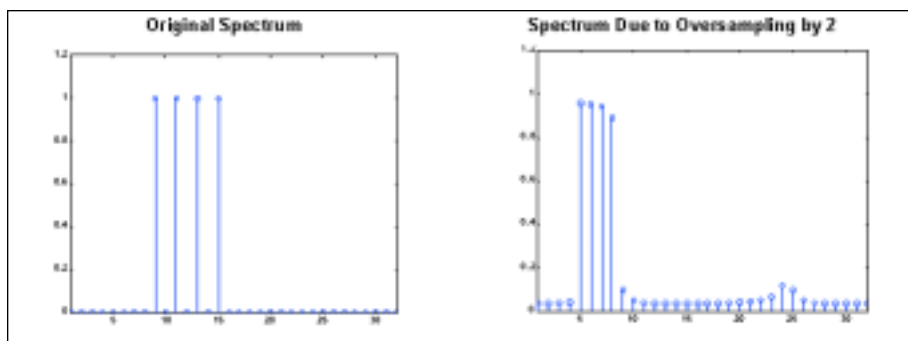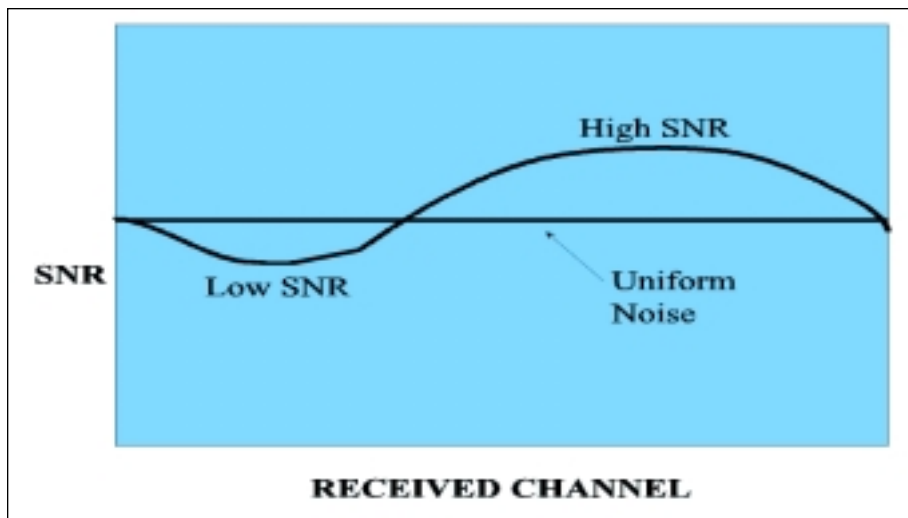
Impulse noise

Impulse noise is a common impairment in a communications system arising from motors or lightning. Impulse noise is typically characterized as a short time-domain burst of energy. The burst may be repetitive or may be a single event. In either case, the frequency spectrum from this energy burst is wideband, typically much wider than the channel, but is present for only a short time period.

One of the most important concepts to understand about OFDM and its properties related to the FFT algorithm is how the algorithm changes the nature of the signal. In a single-carrier system, the symbol can be viewed as occupying all of the available frequency spectrum for the time duration of the symbol. A group of symbols then occupies all of the spectrum for the duration of the whole group, but in a time division arrangement.

OFDM, using the FFT, takes symbols and creates these groups directly and then transforms them. They are no longer time-domain multiplexed, they are now frequency-domain multiplexed. The OFDM symbol is now a collection of these source symbols, and this OFDM symbol now has a much longer duration. Each original symbol occupies only a small frequency region, but now occupies that region for the entire OFDM symbol duration. Figure 13 illustrates this concept. For impulses that are short in duration, the impulse energy masks a smaller percentage of time of each OFDM symbol compared to the single carrier case. Impulse noise can therefore have less of an effect on short duration noise.

Carrier interference

Single-carrier interference arises from other sources that may co-exist in the frequency range of interest. These can be generated by nearby circuits or other transmission sources. The single carrier system must handle this interference as a noise source for all information sent. The OFDM system can avoid the frequency region of interference by disabling or turning off the affected subcarriers. Narrowband modulated sources of interference can be consid-

Figure 12. Uniform and Non-uniform noise and SNR. OFDM can tailor its modulation to the shape of the noise spectrum.

ered similar to carrier interference in their impairment.

Phase noise

Noise can also be added to the signal through a frequency-conversion stage. The local oscillator used in the converter will inherently have some phase noise (uncertainty of actual frequency or phase of the signal) that will be transferred to the desired signal. Figure 14 shows the effect of phase noise on a local oscillator. Phase noise is shaped and is primarily concentrated near the carrier (or center frequency) of the signal.

An OFDM signal set contains multiple subcarriers, each of which is a smaller percentage of the total frequency bandwidth than in a single carrier system. As a result, phase noise is a smaller percentage of the bandwidth in a single-carrier system.

For this reason, phase noise degrades the performance of an OFDM system more than in a single carrier system. Phase noise effects in an OFDM system can be separated into two categories: phase noise maintained within one subcarrier spacing, and phase noise that extends across subcarrier spacings. Phase noise that extends across subcarrier spacings is considered extreme and results in demodulation errors. Phase noise within one subcarrier spacing essentially has a similar but scaled effect as for the single carrier system. The phase noise results in phase uncertainty in the constellation point producing an arc-shaped noise pattern in the constellation of each subcarrier.

In order to help the OFDM system handle phase noise, pilot subcarriers are often used. These pilot subcarriers

are generated by the IFFT and can be used to provide a stable phase reference for the receiver circuitry. Adding these pilots lowers the available data rate of the system because these subcarriers are no longer available to transmit data.

Non-linear circuits in the transmitter and receiver

All transmitters and receivers in communications systems contain devices such as amplifiers and mixers that have non-linear transfer functions. These non-linearities create an additional performance limitation. The receiver performance is typically limited by distortion generated in the input amplifier or mixer in the presence of strong undesired signals. The transmitter performance is limited primarily by power amplifier linearity. An OFDM signal is made up of multiple simultaneous signals that, for a given average power, have a higher peak signal level. OFDM signals result in an increase in the peak-to-average ratio (PAR) of the signal. For multi-carrier systems, the PAR value is often expressed in terms of statistics because the probability that all subcarriers will simultaneously reach peak amplitude is low, even though the simultaneous peak amplitude value is large. These higher peak amplitude levels will create more severe distortion than a single carrier case even if the average power levels of each are the same. The higher distortion will increase the SNR needed to maintain adequate performance. Linearity requirements in both the receiver and transmitter must be adjusted or "backed off" to account for this increase in PAR value. The PAR value, and also the amount of linearity compensation, will depend on a number of parameters including the number of subcarriers and the level of SNR that must be maintained.

Modern applications

OFDM has been chosen for several current and future communications systems all over the world. It is well-suited for systems in which the channel characteristics make it difficult to maintain adequate communications link performance. Asynchronous digital subscriber line (ADSL) provides a method of delivering high speed data over the phone line. The system uses OFDM techniques, calling their variation discrete multi-tone (DMT). DMT includes fea-
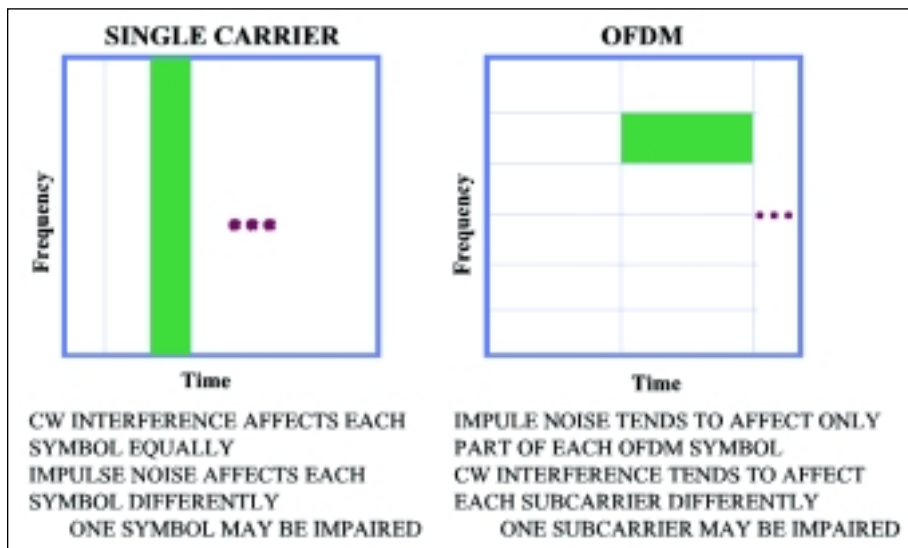

Figure 13. Comparison of single carrier versus OFDM spectrum.

tures for allowing the removal of subcarriers and for adjusting modulation format (from 1 to 15 bits per symbol) on a per sub-carrier basis to best suit the transmission channel characteristics. The system also permits "dynamic allocation" of these parameters.

European digital television is based on the DVB-T (digital video broadcast - terrestrial) standard that uses either 2048 (2K) or 8192 (8K) subcarriers within a standard 8 MHz TV channel. The system specifications and coding were specifically designed to allow multipoint repeater signaling that creates co-channel signals. Discussions are ongoing in the U.S. to look at a similar system and Japan is close to adopting a similar standard for their future digital TV broadcast system.

The next generation of radio broadcast may also make use of OFDM techniques. In the U.S., the system under consideration will initially "co-exist" in the same frequency slot as the current analog broadcast. OFDM allows the system designers to shape the digital spectrum by disabling the subcarriers that correspond to the current analog spectrum during the co-existence period. After the co-existence period the subcarriers can be enabled and the subsequent data rate increased.

Various high-speed wireless networking standards in the 5 GHz frequency region employ OFDM modulation. The U.S. IEEE 802.11a and European ETSI Hiperlan/2 standards utilize similar physical layer structures with 64-carrier OFDM and modulation ranging from BPSK to 64-QAM per subcarrier. Various data rates from 6 to 54 Mbps are possible. OFDM works well in home and office environments for handling wall reflections and movement within the structure.

Conclusions

OFDM techniques are quickly becoming a popular method for advanced communications networks. Advances in VLSI technology have made it possible to efficiently implement an FFT block in hardware. Despite the advantages OFDM can offer, the hardware to imple-
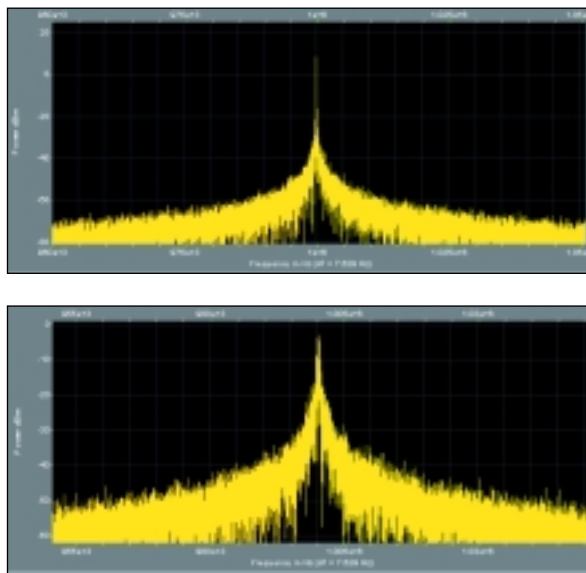

Figure 14. Phase noise on a LO. The upper picture shows a signal with very little phase noise, and the lower picture shows the same signal with phase noise added

ment it can still make up a sizeable and expensive portion of the design. OFDM should not be considered for every communication system because of its increased complexity and higher transmitter and receiver demands. However, for certain systems, modern digital signal processing techniques now make it possible to use this modulation system to improve the reliability of the communications link.

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