OFDM as a possible modulation technique for multimedia applications in the range of mm waves

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Abstract - **In this paper is given an overview of a multiple carrier modulation technique known as OFDM (Orthogonal Frequency Division Multiplex). It focuses on problems that are specific for its use in the future mobile multimedia communications (MMC) in the range of 60 GHz.**

I Introduction

Multimedia is effectively an infrastructure technology with widely different origins in computing, telecommunications, entertainment and publishing. New applications are emerging, not just in the wired environment, but also in the mobile one. At present, only low bit-rate data services are available to the mobile users. However, demands of the wireless multimedia broadband system are anticipated within both public and private sector.

This report discusses possible ways to enable multimedia communications in the mobile environment. Multimedia communication has a rather large demands upon bandwidth and quality of service (QoS) compared to what is available today to the mobile user. Bitrates for multimedia span from a few Kb/s, for voice, to about 20 Mb/s for HDTV, or even more in the peaks.

When solving this problem, first question is how to put this large bit stream on air with sufficient QoS guaranties, i.e. which modulation can compromise all contradicting requirements in the best manner. The radio environment is harsh, due to the many reflected waves and other effects. Using adaptive equalization techniques at the receiver could be the solution, but there are practical difficulties in operating this equalization in real-time at several Mb/s with compact, low-cost hardware. A promising candidate that eliminates a need for the complex equalizers is the Orthogonal Frequency Division Multiplexing (OFDM), a multiple carrier modulation technique. This modulation system is described, its applications and drawbacks are outlined, along with some important characteristics of OFDM and single-carrier techniques.

The second question is how to deal with a number of users wanting to exploit one communication medium. Some way of sharing the common medium is needed. Multiple access techniques are quite developed for the single carrier modulations (e.g. TDMA, FDMA), but there is nothing in the literature concerning OFDM. Downlink is easy, but uplink poses serious troubles on the system designer.

II The mobile environment

The main problem with reception of radio signals is fading caused by multipath propagation. Also, there are intersymbol interference (ISI), shadowing, interference. This makes link quality vary. Further constraints are limited bandwidth, low power consumption, network management and multi-cellular operation.

As a result of the multipath propagation, there are many reflected signals, which arrive at the receiver at different times. Delayed signals are the result of reflections from terrain features such as trees, hills or mountains, or objects such as people, vehicles or buildings. These echoes cause ISI. Combined, these signals can produce fading. Some of these reflections can be avoided by using a directional antenna (current trend is simple antennas), but it is impossible to use them for a mobile user. A solution could be usage of antenna arrays, but this technology is still being developed.

A characteristic of frequency selective fading is that some frequencies are enhanced, whereas others are attenuated. If there is a mobile reception, then the relative lengths and attenuations of the various reception paths will change with time. A narrowband signal will vary in quality as the peaks and the troughs of the frequency response move around in frequency domain. There will also be a noticeable variation in phase response, which will affect all systems using phase as a means of signalling .

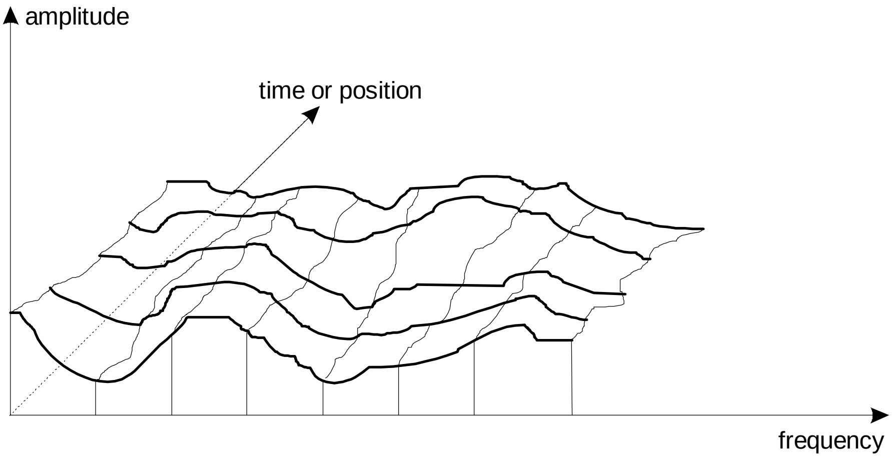

Fig 1. Typical frequency response of a channel suffering from multipath propagation. The frequency response will vary with both time and position. Frequency selective attenuation is clearly present.

Now consider a signal which is of greater bandwidth. Some parts of the signal may suffer from constructive interference and be enhanced in level, whereas others may suffer from destructive interference and be attenuated, sometimes to the point of extinction. In general, frequency components that are close together will suffer variations in signal strength that are strongly correlated. The correlation (or coherence) is used as a measure of this phenomenon. There is no standard definition of the correlation bandwidth. For a narrowband signal, distortion is usually minimised if the bandwidth is less than the correlation bandwidth of the channel, because all frequencies in the band are usually distorted in the same way. There is, however, a significant chance that the signal will be subject to severe attenuation on some occasions. A signal which occupies a wider bandwidth, greater than correlation bandwidth, will be subject to more distortion, but will suffer less variation in total received power, even if it is subject to significant levels of multipath propagation. This comes from the fact that variation averages out if the bandwidth is much larger than the correlation bandwidth, because different parts of the band suffer different levels of distortion. One can often find following formula for correlation bandwidth B_c, where D is the RMS value of delay spread (not average).

$$B_c \approx \frac{1}{D}$$

If we look at the temporal response of the channel, we see a number of echoes present. There are many different types of echo environment, which are typical of different outdoor/indoor areas. This range of delay can be measured and then processed to get statistical parameters. Different studies use the total range of delay, or the average delay. Whichever is chosen, the inverse of this leads to a good approximation for the correlation bandwidth.

Spread spectrum techniques are robust against fading and interference, but they set forth impossible demands on the existing technology – for instance, if a user needs a speed of 20Mb/s on air and the spreading factor is 128 (today's typical), this results in 2.56 GB/s which have to processed in real-time and have impracticably large bandwidth. Besides that, they have difficulty with the near-far effect and have a large power-consumption.

Single-carrier techniques are vulnerable to fading and multipath propagation, especially in the case of very high bitrates. Improvements can be made with frequency equalization and directional antennas, which can also be used to improve multicarrier techniques.

Recently, research and development of the OFDM have received considerable attention and have made a great deal of progress in Europe. OFDM is a wideband modulation scheme that is specifically able to cope with the problems of the multipath reception. This is achieved by transmitting many narrowband overlapping digital signals in parallel, inside one wide band. Increasing the number of parallel transmission channels reduces the data rate that each individual carrier must convey, and that lengthens the symbol period. As a result, the delay time of reflected waves is suppressed to within 1 symbol time.

The 60 GHz band

The scarcity of spectrum and the new technical possibilities in recent years have drawn attention all over the world to the millimetre band. It has become a hot topic as a research area for broadband communications.

The low mm-wave band from 20-60 GHz, which is nearly unused and allows for large bandwidth applications, combines the advantages of infrared (enough free bandwidth and UHF (good coverage). Use of the area around 60 GHz is encouraged for the following reasons.

- The coherence bandwidth of a 60 GHz link is several MHz. [1]
- There is enough unused space for the multimedia needs (5 GHz) [2]. This frequency region is not in use by any other medium, so to every user can be allocated a large bandwidth, i.e. bitrates of an order of 155Mb/s are possible, thus a potential exists to support broadband service access, which is especially relevant because of the advent of the Broadband Digital Network (B-ISDN).
- Systems operating particularly in the 60 GHz frequency band can have a small reuse distance, because of the oxygen absorption at the rate of 14 dB/km [1]. Usually, this is a disadvantage for many applications; however, this high attenuation over the propagation path creates a natural barrier for cochannel interference in the mobile cellular system. Thus, frequency reuse is easy.
- Wavelength is as little as 5 mm. This enables crating of small antenna's and other parts of the radio-part of the system. This size of communication equipment makes it easy for wearing.

A major drawback of this frequency region is the fact that the technology for the transceivers will be expensive in the early stages. If used indoor, the mm-wave radio channel shows adverse frequency selective multipath characteristics due to the highly reflective indoor environment, which results in severe signal dispersion and limits the maximum usable symbol rate. It is worth mentioning that no definitive evidence of any hazards has been shown to date to the general public arising from the prolonged exposure in fields of less than 10 mW/cm^2 in the mm-waves.

There is a lot of fundamental investigation needed in this area, e.g. propagation modeling for 60 GHz, effects of antenna diversity, technology development, etc.
For the final choice between OFDM and single-carrier modulation, one needs knowing the channel properties at 60 GHz. Measurements and models can hardly be found in the literature. These properties have to be built in the simulation model, which could then be used for evaluating modulation technique candidates for the mobile multimedia communication.

III OFDM

OFDM history

The concept of using parallel data transmission by means of frequency division multiplexing (FDM) was published in mid 60s [3,4]. Some early development can be traced back in the 50s. A U.S. patent was filled and issued in January, 1970. The idea was to use parallel data streams and FDM with overlapping subchannels to avoid the use of high speed equalization and to combat impulsive noise, and multipath distortion as well as to fully use the available bandwidth. The initial applications were in the military communications. In the telecommunications field, the terms of discrete multi-tone (DMT), multichannel modulation and multicarrier modulation (MCM) are widely used and sometimes they are interchangeable with OFDM. In OFDM, each carrier is orthogonal to all other carriers. However, this condition is not always maintained in MCM. OFDM is an optimal version of multicarrier transmission schemes.

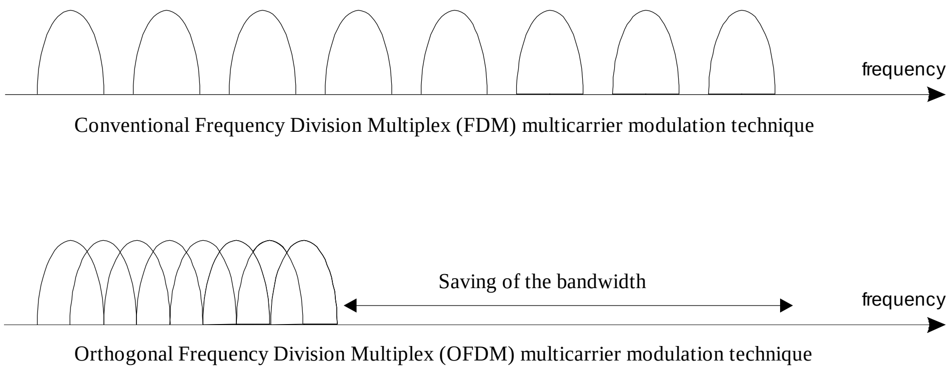

Fig. 2 Comparison of the bandwidth utilization for FDM and OFDM

For a large number of subchannels, the arrays of sinusoidal generators and coherent demodulators required in a parallel system become unreasonably expensive and complex. The receiver needs precise phasing of the demodulating carriers and sampling times in order to keep crosstalk between subchannels acceptable. Weinstein and Ebert [5] applied the discrete Fourier transform (DFT) to parallel data transmission system as part of the modulation and demodulation process. In addition to eliminating the banks of subcarrier oscillators and coherent demodulators required by FDM, a completely digital implementation could be built around special-purpose hardware performing the fast Fourier transform (FFT). Recent advances in VLSI technology enable making of high-speed chips that can perform large size FFT at affordable price.

In the 1980s, OFDM has been studied for high-speed modems, digital mobile communications and high-density recording. One of the systems used a pilot tone for stabilizing carrier and clock frequency control and trellis coding was implemented. Various fast modems were developed for telephone networks.

In 1990s, OFDM has been exploited for wideband data communications over mobile radio FM channels, high-bit-rate digital subscriber lines (HDSL, 1.6 Mb/s), asymmetric digital subscriber lines (ADSL, 1,536 Mb/s), very high-speed digital subscriber lines (VHDSL, 100 Mb/s), digital audio broadcasting (DAB) and HDTV terrestrial broadcasting.

Qualitative description of OFDM

In multimedia communication, a demand emerges for high-speed, high-quality digital mobile portable reception and transmission. A receiver has to cope with a signal that is often weaker than desirable and that contains many echoes. Simple digital systems do not work well in the multipath environment.

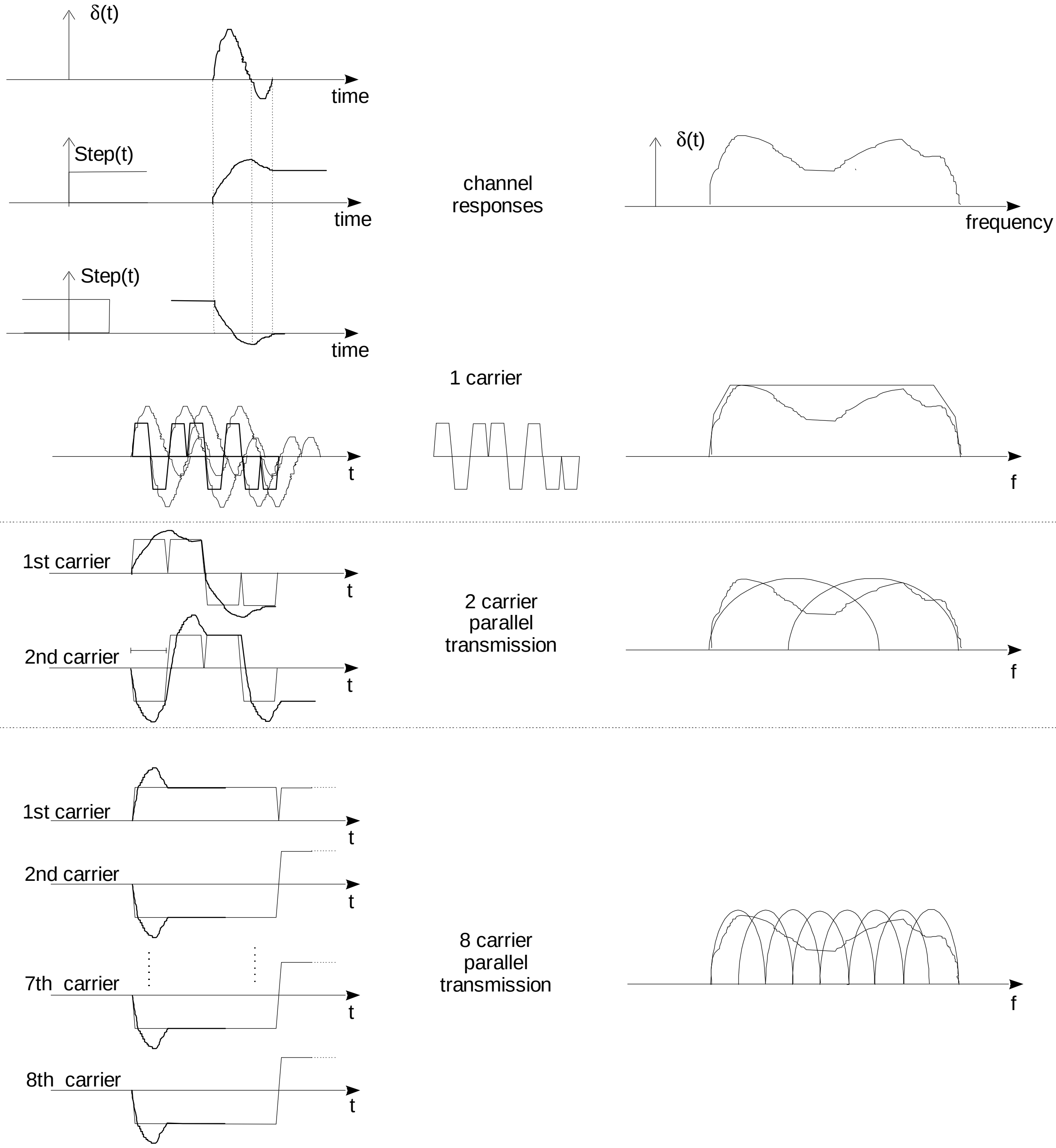

Fig. 3 The effect of adopting a multicarrier system. For a given overall data rate, increasing the number of carriers reduces the data rate that each individual carrier must convey, and hence (for a given modulation system) lengthens the symbol period. This means that the intersymbol interference affects a smaller percentage of each symbol as the number of carriers and hence the symbol period increases (after [10[DM1]]). For example, on the picture is shown a

8 bit long part of a data sequence. For a single carrier system, the responses of individual bits are overlapping, thus creating ISI. Multicarrier system is robust against these physical effects.

In a conventional serial data system, the symbols are transmitted sequentially, with the frequency spectrum of each data symbol allowed to occupy the entire available bandwidth. In a parallel data transmission system several symbols are transmitted at the same time, what offers possibilities for alleviating many of the problems encountered with serial systems.

In OFDM, the data is divided among large number of closely spaced carriers. This accounts for the “frequency division multiplex” part of the name. This is *not* a multiple access technique, since there is no common medium to be shared. The entire bandwidth is filled from a single source of data. Instead of transmitting in serial way, data is transferred in a parallel way. Only a small amount of the data is carried on each carrier, and by this lowering of the bitrate per carrier (not the total bitrate), the influence of intersymbol interference is significantly reduced. In principle, many modulation schemes could be used to modulate the data at a low bit rate onto each carrier.

It is an important part of the OFDM system design that the bandwidth occupied is greater than the correlation bandwidth of the fading channel. A good understanding of the propagation statistics is needed to ensure that this condition is met. Then, although some of the carriers are degraded by multipath fading, the majority of the carriers should still be adequately received. OFDM can effectively randomize burst errors caused by Rayleigh fading, which comes from interleaving due to paralellisation. So, instead of several adjacent symbols being completely destroyed, many symbols are only slightly distorted. Because of dividing an entire channel bandwidth into many narrow subbands, the frequency response over each individual subband is relatively flat. Since each subchannel covers only a small fraction of the original bandwidth, equalization is potentially simpler than in a serial data system. A simple equalization algorithm can minimize mean-square distortion on each subchannel, and the implementation of differential encoding may make it possible to avoid equalization altogether [5]. This allows the precise reconstruction of majority of them, even without forward error correction (FEC).

In addition, by using a guard interval the sensitivity of the system to delay spread can be reduced [8].

In a classical parallel data system, the total signal frequency band is divided into N non-overlapping frequency subchannels. Each subchannel is modulated with a separate symbol and, then, the N subchannels are frequency multiplexed. There are three schemes that can be used to separate the subbands:

1. Use filters to completely separate the subbands. This method was borrowed from the conventional FDM technology. The limitation of filter implementation forces the bandwidth of each subband to be equal to $(1+\alpha)f_m$, where α is the roll-off factor and f_m is the Nyquist bandwidth. Another disadvantage is that it is difficult to assemble a set of matched filter when the number of carriers is large.
2. Use staggered QAM to increase the efficiency of band usage. In this way the individual spectra of the modulated carriers still use an excess bandwidth, but the are overlapped at the 3 dB frequency. The advantage is that the composite spectrum is flat. The separability or orthogonality is achieved by staggering the data (offset the data by half a symbol). The requirement for filter design is less critical than that for the first scheme.
3. Use discrete Fourier transform (DFT) to modulate and demodulate parallel data. The individual spectra are now *sinc* functions and are not band limited. The FDM is achieved, not by bandpass filtering, but by baseband processing. Using this method, both transmitter and receiver can be implemented using efficient FFT techniques that reduce the number of operations from N^2 in DFT, down to NlogN.

OFDM can be simply defined as a form of multicarrier modulation where its carrier spacing is carefully selected so that each subcarrier is orthogonal to the other subcarriers. As is well known, orthogonal signals can be separated at the receiver by correlation techniques; hence, intersymbol interference among channels can be eliminated. Orthogonality can be achieved by carefully selecting carrier spacing, such as letting the carrier spacing be equal to the reciprocal of the useful symbol period. Mathematical deduction of the orthogonal carrier frequencies is given in [3].

In order to occupy sufficient bandwidth to gain advantages of the OFDM system, it would be good to group a number of users together to form a wideband system, in order to interleave data in time and frequency (depends how broad is one user signal).

The importance of coding

The distribution of the data over many carriers means that selective fading will cause some bits to be received in error while others are received correctly. By using an error-correcting code, which adds extra bits at the transmitter, it is possible to correct many or all of the bits that were incorrectly received. The information carried by one of the degraded carriers is corrected, because other information, which is related to it by the error-correcting code, is transmitted in a different part of the multiplex (and, it is hoped, will not suffer from the same deep fade). This accounts for the “coded” part of the name COFDM.

There are many types of error correcting codes, which could be used.

The importance of orthogonality

The “orthogonal” part of the OFDM name indicates that there is a precise mathematical relationship between the frequencies of the carriers in the system. In a normal FDM system, the many carriers are spaced apart in such way that the signals can be received using conventional filters and demodulators. In such receivers, guard bands have to be introduced between the different carriers (Fig. 2.), and the introduction of these guard bands in the frequency domain results in a lowering of the spectrum efficiency.

It is possible, however, to arrange the carriers in an OFDM signal so that the sidebands of the individual carriers overlap and the signals can still be received without adjacent carrier interference. In order to do this the carriers must be mathematically orthogonal. The receiver acts as a bank of demodulators, translating each carrier down to DC, the resulting signal then being integrated over a symbol period to recover the raw data. If the other carriers all beat down to frequencies which, in the time domain, have a whole number of cycles in the symbol period (τ), then the integration process results in zero contribution from all these carriers. Thus the carriers are linearly independent (i.e. orthogonal) if the carrier spacing is a multiple of $1/\tau$.

Mathematically, suppose we have a set of signals **y** , where ψ_p is the p-th element in the set. The signals are orthogonal if

$$\int_a^b \Psi_p(t)\Psi_q^*(t)dt = \begin{cases} K & for\ p = q \\ 0 & for\ p \neq q \end{cases},$$

where the * indicates the complex conjugate and interval [a,b] is a symbol period. A fairly simple mathematical proof exists, that the series *sin*(*mx*) for m=1,2,… is orthogonal over the interval $-\pi$ to π. Much of transform theory makes the use of orthogonal series, although they are by no means the only example.

Mathematical description of OFDM

After the qualitative description of the system, it is valuable to discuss the mathematical definition of the modulation system. This allows us to see how the signal is generated and how receiver must operate, and it gives us a tool to understand the effects of imperfections in the transmission channel. As noted above, OFDM transmits a large number of narrowband carriers, closely spaced in the frequency domain. In order to avoid a large number of modulators and filters at the transmitter and complementary filters and demodulators at the receiver, it is desirable to be able to use modern digital signal processing techniques, such as fast Fourier transform (FFT).

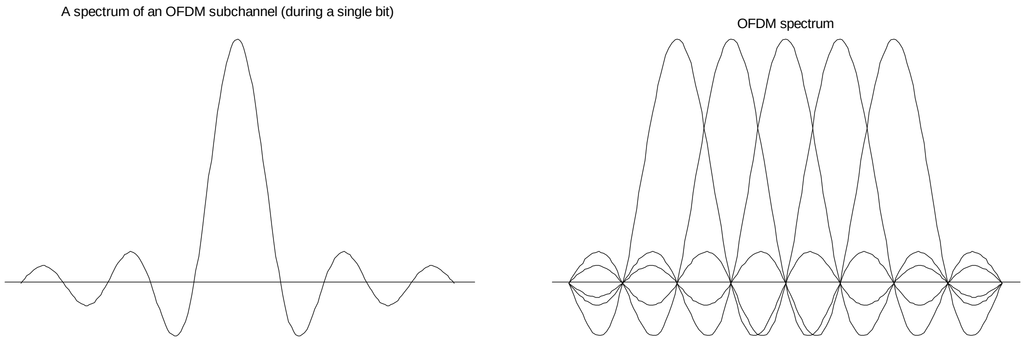

Fig. 4 Examples of OFDM spectrum (a) a single subchannel, (b) 5 carriers
At the central frequency of each subchannel, there is no crosstalk from other subchannels

Mathematically, each carrier can be described as a complex wave:

$$s_c(t) = A_c(t) e^{j\left[w_c t + f_c(t)\right]} \tag{1}$$

The real signal is the real part of $s_c(t)$. Both $A_c(t)$ and $f_c(t)$, the amplitude and phase of the carrier, can vary on a symbol by symbol basis. The values of the parameters are constant over the symbol duration period τ.

OFDM consists of many carriers. Thus the complex signals $s_s(t)$ (Fig. 4) is represented by:

$$s_s(t) = \frac{1}{N} \sum_{n=0}^{N-1} A_N(t) e^{j\left[w_n t + f_n(t)\right]} \tag{2}$$

where

$$w_n = w_0 + n\Delta w$$

This is of course a continuous signal. If we consider the waveforms of each component of the signal over one symbol period, then the variables $A_c(t)$ and $f_c(t)$ take on fixed values, which depend on the frequency of that particular carrier, and so can be rewritten:

$$f_n(t) \Rightarrow f_n$$
$$A_n(t) \Rightarrow A_n$$

If the signal is sampled using a sampling frequency of 1/T, then the resulting signal is represented by:

$$s_s(kT)=\frac{1}{N}\sum_{n=0}^{N-1}A_n e^{j\left[\left(w_0+n\Delta w\right)kT+f_n\right]} \qquad (3)$$

At this point, we have restricted the time over which we analyse the signal to N samples. It is convenient to sample over the period of one data symbol. Thus we have a relationship:

$$\tau=NT$$

If we now simplify eqn. 3, without a loss of generality by letting $\omega_0=0$, then the signal becomes:

$$s_s(kT)=\frac{1}{N}\sum_{n=0}^{N-1}A_n e^{j f_n} e^{j(n\Delta w)kT} \qquad (4)$$

Now Eq. 4 can be compared with the general form of the inverse Fourier transform:

$$g(kT)=\frac{1}{N}\sum_{n=0}^{N-1}G\left(\frac{n}{NT}\right)e^{j2pnk/N} \qquad (5)$$

In eq. 4, the function $A_n e^{j f_n}$ is no more than a definition of the signal in the sampled frequency domain, and *s(kT)* is the time domain representation. Eqns. 4 and 5 are equivalent if:

$$\Delta f=\frac{\Delta w}{2p}=\frac{1}{NT}=\frac{1}{t} \qquad (6)$$

This is the same condition that was required for orthogonality (see *Importance of orthogonality*). Thus, one consequence of maintaining orthogonality is that the OFDM signal can be defined by using Fourier transform procedures.

The Fourier transform

The Fourier transform allows us to relate events in time domain to events in frequency domain. There are several version of the Fourier transform, and the choice of which one to use depends on the particular circumstances of the work.

The conventional transform relates to continuous signals which are not limited to in either time or frequency domains. However, signal processing is made easier if the signals are sampled. Sampling of signals with an infinite spectrum leads to aliasing, and the processing of signals which are not time limited can lead to problems with storage space.

To avoid this, the majority of signal processing uses a version of the discrete Fourier transform (DFT) [6,7]. The DFT is a variant on the normal transform in which the signals are sampled in both time and the frequency domains. By definition, the time waveform must repeat continually, and this leads to a frequency spectrum that repeats continually in the frequency domain. [5]

The fast Fourier transform (FFT) is merely a rapid mathematical method for computer applications of DFT. It is the availability of this technique, and the technology that allows it to be implemented on integrated circuits at a reasonable price, that has permitted OFDM to be developed as far as it has. The process of transforming from the time domain representation to the frequency domain representation uses the Fourier transform itself, whereas the reverse process uses the inverse Fourier transform.

The use of the FFT in OFDM

The main reason that the OFDM technique has taken a long time to become a prominence has been practical. It has been difficult to generate such a signal, and even harder to receive and demodulate the signal. The hardware solution, which makes use of multiple modulators and demodulators, was somewhat impractical for use in the civil systems.

The ability to define the signal in the frequency domain, in software on VLSI processors, and to generate the signal using the inverse Fourier transform is the key to its current popularity. The use of the reverse process in the receiver is essential if cheap and reliable receivers are to be readily available. Although the original proposals were made a long time ago [5], it has taken some time for technology to catch up.

At the transmitter, the signal is defined in the frequency domain. It is a sampled digital signal, and it is defined such that the discrete Fourier spectrum exists only at discrete frequencies. Each OFDM carrier corresponds to one element of this discrete Fourier spectrum. The amplitudes and phases of the carriers depend on the data to be transmitted. The data transitions are synchronised at the carriers, and can be processed together, symbol by symbol (Fig. 5).

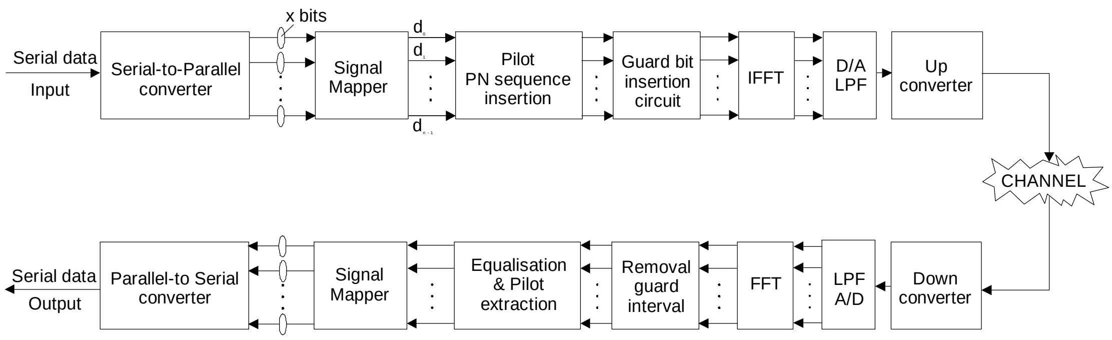

Fig. 5 Block diagram of an OFDM system using FFT, pilot PN sequence and a guard bit insertion [9]

The definition of the (N-point) discrete Fourier transform (DFT) is:

$$X_p[k] = \sum_{n=0}^{N-1} x_p[n] e^{-j(2p/N)kn} \qquad \text{(DFT)} \tag{7}$$

and the (N-point) inverse discrete Fourier transform (IDFT):

$$x_p[n] = \frac{1}{N} \sum_{k=0}^{N-1} X_p[k] e^{j(2p/N)kn} \qquad \text{(IDFT)} \tag{8}$$

A natural consequence of this method is that it allows us to generate carriers that are orthogonal. The members of an orthogonal set are linearly independent.

Consider a data sequence (d_0, d_1, d_2, …, d_{N-1}), where each d_n is a complex number $d_n=a_n+jb_n$. (a_n, b_n=±1 for QPSK, a_n, b_n=±1, ±3 for 16QAM, …)

$$D_m = \sum_{n=0}^{N-1} d_n e^{-j(2pnm/N)} = \sum_{n==0}^{N-1} d_n e^{-j2pf_n t_m} \qquad k=0,1,2,\ldots,N-1 \tag{9}$$

where f_n=n/(NΔT), t_k=kΔt and Δt is an arbitrarily chosen symbol duration of the serial data sequence d_n. The real part of the vector D has components

$$Y_m = \mathrm{Re}\{D_m\} = \sum_{n=0}^{N-1}\left[\left(a_n \cos(2\pi f_n t_m) + b_n \sin(2\pi f_n t_m)\right)\right], \qquad k=0,1,\ldots,N-1 \tag{10}$$

If these components are applied to a low-pass filter at time intervals Δt, a signal is obtained that closely approximates the frequency division multiplexed signal

$$y(t) = \sum_{n=0}^{N-1}\left[\left(a_n \cos(2\pi f_n t_m) + b_n \sin(2\pi f_n t_m)\right)\right], \qquad 0 \le t \le N\Delta t \tag{11}$$

Fig. 5 illustrates the process of a typical FFT-based OFDM system. The incoming serial data is first converted form serial to parallel and grouped into *x* bits each to form a complex number. The number *x* determines the signal constellation of the corresponding subcarrier, such as 16 QAM or 32QAM. The complex numbers are modulated in the baseband by the inverse FFT (IFFT) and converted back to serial data for transmission. A guard interval is inserted between symbols to avoid intersymbol interference (ISI) caused by multipath distortion. The discrete symbols are converted to analog and low-pass filtered for RF upconversion. The receiver performs the inverse process of the transmitter. One-tap equalizer is used to correct channel distortion. The tap-coefficients of the filter are calculated based on the channel information.

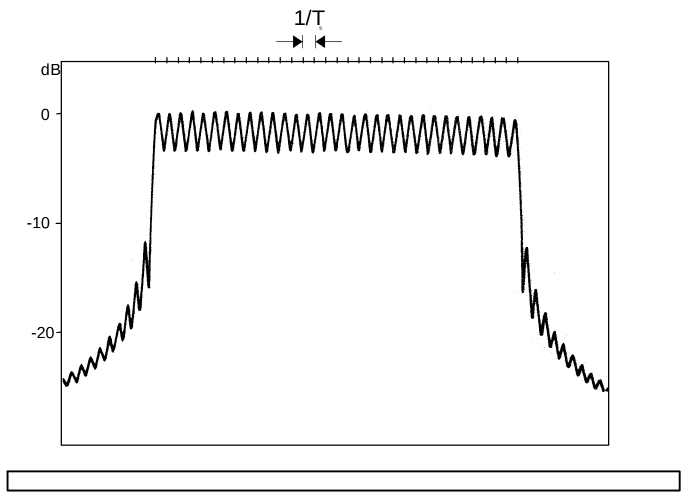

Fig. 6 Example of the power spectral density of the OFDM signal with a guard interval $\Delta = T_S/4$ (number of carriers N=32) [12]

Fig 4a shows the spectrum of an OFDM subchannel and Fig. 4b and Fig. 6 present composite OFDM spectrum. By carefully selecting the carrier spacing, the OFDM signal spectrum can be made flat and the orthogonality among the subchannels can be guaranteed.

Guard interval and its implementation

The orthogonality of subchannels in OFDM can be maintained and individual subchannels can be completely separated by the FFT at the receiver when there are no intersymbol interference (ISI) and intercarrier interference (ICI) introduced by transmission channel distortion. In practice these conditions can not be obtained. Since the spectra of an OFDM signal is not strictly band limited (*sinc(f)* function), linear distortion such as multipath cause each subchannel to spread energy into the adjacent channels and consequently cause ISI. A simple solution is to increase symbol duration or the number of carriers so that distortion becomes insignificant. However, this method may be difficult to implement in terms of carrier stability, Doppler shift, FFT size and latency.

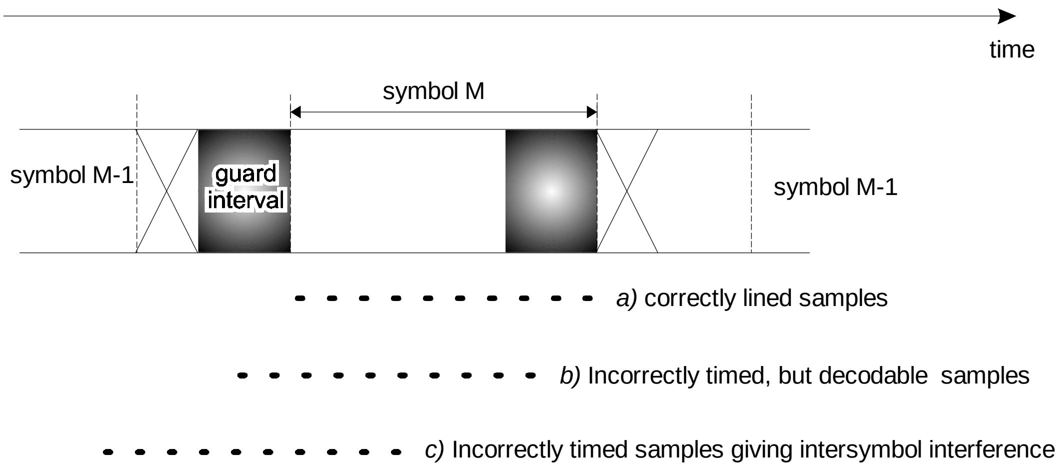

Fig. 7 The effect on the timing tolerance of adding a guard interval. With a guard interval included in the signal, the tolerance on timing the samples is considerably more relaxed.

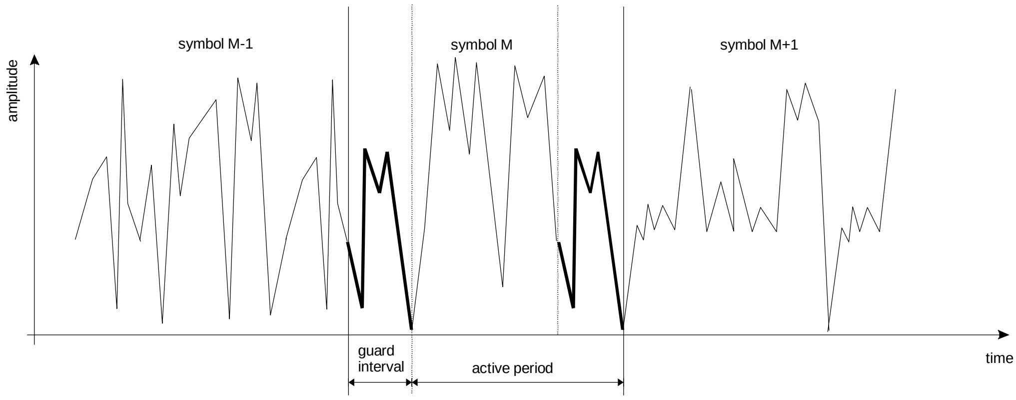

Fig. 8 Example of the guard interval. Each symbol is made up of two parts. The whole signal is contained in the active symbol (shown highlighted for the symbol M) The last part of which (shown in bold) is also repeated at the start of the symbol and is called the guard interval

One way to prevent ISI is to create a cyclically extended guard interval (Fig. 7, 8), where each OFDM symbol is preceded by a periodic extension of the signal itself. The total symbol duration is $T_{total}=T_g+T$, where T_g is the guard interval and T is the useful symbol duration. When the guard interval is longer than the channel impulse response (Fig. 3), or the multipath delay, the ISI can be eliminated. However, the ICI, or in-band fading, still exists. The ratio of the guard interval to useful symbol duration is application-dependent. Since the insertion of guard interval will reduce data throughput, T_g is usually less than $T/4$.

The reasons to use a cyclic prefix for the guard interval are:

- to maintain the receiver carrier synchronization ; some signals instead of a long silence must always be transmitted;
- cyclic convolution can still be applied between the OFDM signal and the channel response to model the transmission system.

Application of OFDM: Coded OFDM for Digital Audio Broadcast (DAB) [10]

In DAB, staggered quadrature phase shift keying (Π/4 QPSK) is used, with differential coding. Main channel code is convolutional error correcting code, with a Viterbi decoder., some of the higher priority data is precoded with a block code for additional security. These coding options have been tailored to audio and signaling data, which is being broadcast.

The data is interleaved, both in frequency and time. The error correction process works best if the errors in the incoming data are random.

The addition of the guard interval allows the system to cope with echoes of moderate duration, and with small inaccuracies in the receiver.

IV Choice of the key elements

Useful symbol duration

The useful symbol duration T affects the carrier spacing and coding latency. To maintain the data throughput, a longer useful symbol duration results in increase of the number of carriers and the size of FFT (assuming the constellation is fixed). In practice, carrier offset and phase stability may affect how close two carriers can be placed. If the application is for the mobile reception, the carrier spacing must be large enough to make the Doppler shift negligible. Generally, the useful symbol duration should be chosen so that the channel is stable for the duration of a symbol.

Number of carriers

The number of subcarriers can be determined based on the channel bandwidth, data throughput and useful symbol duration.

$$N = \frac{1}{T}$$

The carriers are spaced by the reciprocal of the useful symbol duration. The number of carriers corresponds to the number of complex points being processed in FFT. For HDTV applications, the number of subcarriers are in the range of several thousands, so as to accommodate the data rate and guard interval requirement.

Modulation scheme

The modulation scheme in an OFDM system can be selected based on the requirement of power or spectrum efficiency. The type of modulation can be specified by the complex number $d_n=a_n+jb_n$, defined in section *The use of FFT in OFDM*. The symbols a_n and b_n can be selected to (±1, ±3) for 16QAM and ±1 for QPSK. In general, the selection of the modulation scheme applying to each subchannel depends solely on the compromise between the data rate requirement and transmission robustness. Another advantage of OFDM is that different modulation schemes can be used on different subchannels for layered services.

Coded OFDM

By using frequency and time diversity OFDM provides a means to transmit data in a frequency selective channel. However, it does not suppress fading itself. Depending on their position in the frequency domain, individual subchannels could be affected by fading. This requires the use of channel coding to further protect transmitted data. Among those channel techniques, trellis coded modulation (TCM), combined with frequency and time interleaving is considered the most effective means for a selective fading channel.

TCM combines coding and modulation to achieve a high coding gain without affecting the bandwidth of the signal. In a TCM encoder, each symbol of n bits is mapped into constellation of $n+1$ bits, using a set-partitioning rule. This process increases the constellation size and effectively adds additional redundancy to the signal. A TCM code can be decoded with a soft decision Viterbi decoding algorithm, which exploits the soft decision nature of the received signal. The coding gain for a two-dimensional TCM code over a Gaussian channel is about 3 dB for a bit error rate (BER) of 10^{-5}.

It should be mentioned that one of the advantages of OFDM is that it can convert a wideband frequency selective fading channel into a series of narrowband and frequency non-selective fading subchannels by using parallel and multicarrier transmission. Coding OFDM subcarriers sequentially by using specially designed TCM codes for frequency non-selective fading channel is the major reason for using the COFDM for terrestrial broadcasting. However, the search of the best TCM code is still ongoing.

Although trellis codes produce improvements in the signal-to-noise ratio (S/N), they do not perform well with impulsive or burst noise. In general, transmission errors have a strong time/frequency correlation. Interleaving plays an essential role in channel coding by providing diversity in the time domain. Interleaving breaks the correlation and enables the decoder to eliminate or reduce local fading throughout the band and over the whole depth of the time interleaving. Interleaving depth should be enough to break long straight errors.

Flexibility and scalability

Based on the information theory, the channel capacity is a function of the signal-to-noise ratio and channel bandwidth. The concept of graceful degradation has been implemented in the analog TV systems. It is believed that the joint source/channel coding is the best way to achieve flexibility and scalability. COFDM has been considered very flexible for the layered and scaleable transmission. Different groups of COFDM subchannels can be assigned to different orders of modulation, power levels, and channel coding schemes.

V COFDM performance expectations

The following expectations are based on the research for the digital terrestrial television broadcasting [9].

It should be noted that for the additive white Gaussian channel, COFDM and single carrier modulation have comparable performance. However, the broadcasting channel for HDTV consists of various other impairments: random noise, impulse noise, multipath distortion, fading and interference. Also, at the high end of the UHF band the wavelengths are short (around 0.5 m). Thus, characteristics of these holes and peaks in this band are better modeled by a statistical distribution known as a Rayleigh distribution.

Multipath/fading

It is believed that with properly designed guard interval, interleaving and channel coding, COFDM is capable of handling very strong echoes. The BER improvement, which resulted from the multiple echoes, was indicated by the computer simulations and laboratory demonstrations. With the assumption of withstanding strong multipath propagation, COFDM might allow the use of omni-directional antenna in urban areas and mobile reception where C/N is sufficiently high.

In addition to channel fading, time-variant signals caused by transmitter tower swaying, airplane fluttering and even tree swaying generate dynamic ghosts and consequently produce errors in digital transmission. With its parallel transmission structure as well as the use of trellis coding, COFDM systems might present advantages in fading and time-invariant environments.

Phase noise and jitter

A COFDM system is much more affected by carrier frequency errors. A small frequency offset at the receiver compromises the orthogonality between the subchannels, giving a degradation in a system performance that increases rapidly with frequency offset and with the number of subcarriers. Phase noise and jitter can be influenced by the transmitter up-converter and tuner. A possible solution is the use of pilots which can be used to track phase noise in the demodulation. However, this is done under the penalty of reducing the payload data throughput.

Carrier recovery / Equalization

In the severe channel conditions, such as low C/N, strong interference and fading, COFDM signal must be designed to provide robust carrier recovery. Carrier frequency detection could be one of the biggest limitations in COFDM design. The use of pilots and reference symbols are efficient methods for carrier recovery and subchannel equalization. A pilot can be a sine wave or a known binary sequence. A reference symbol can be a chirp or a pseudo-random sequence.

The two-dimensional (time/frequency) signal feature in COFDM makes pilot and reference symbol insertion very flexible. Pilots can be inserted in frequency-domain (fixed carriers) and reference symbols in the time domain (fixed data packets). Because they are transmitted at the predetermined positions in the signal frame structure, it can be captured in the receiver whenever the frame synchronisation is recovered. In a frequency-selective channel, high correlation between the complex fading envelopes of the pilots and data must be ensured. The appropriate complex correction can be obtained by interpolating among the pilots. Cimini [8] reported that interpolation in real and imaginary parts of the complex fading envelopes outperformed the interpolation in amplitude and phase.

For a single carrier system, equalization is done in the time domain. For a QAM system with a N-tap equalizer, there are about N complex multiplication, or 4N real multiplication-accumulation per input symbol. For a VSB system, its symbol rate needs to be twice that of a QAM system for the same data throughput. Assuming the same echo range as for the QAM system, a 2N-tap equalizer is required, which is a computational complexity of about 2N multiplication-accumulations per input symbol.

For a COFDM system, assuming multipath delay is less than the guard interval, a frequency domain one-tap equalizer could be used for each subchannel to correct the amplitude and phase distortions. This corresponds to 4 real multiplication-accumulations per data symbol. Additionally, the FFT operations requires a computational complexity that is proportional to $C^* \log_2(M)$, where M is the size of the FFT and C is the constant between 1.5 to 4 depending on the FFT implementation.

The number of pilots and reference symbols used in a COFDM system determines the trade-off between payload capacity and transmission robustness.

Simulation results indicated that an OFDM system with equalization performed better than that of a single carrier system with a linear equalizer.

Impulse interference

COFDM is more immune to impulse noise than single carrier system, because a COFDM signal is integrated over a long symbol period and the impact of impulse noise is much less than that for single carrier systems. As a matter of fact, the immunity of impulse noise was one of the original motivations for MCM. In a report submitted to the CCITT [11], which presented comparative performance results for asymmetrical duplex V.32 (extended) and multicarrier modems, was shown that the threshold level for the impulse noise, at which errors occur, can be as much as 11 dB higher for MCM than for a single carrier system. Meanwhile, studies indicated that the best approach of impulse noise reduction for OFDM involves a combination of soft and hard error protection.

Peak-to-average ratio

The peak-to-average ratio for a single carrier system depends on the signal constellation and the roll-off factor α of the pulse shaping filter (Gibbs' phenomenon). For the Grand Alliance 8-VSB system (single-carrier rival for the HDTV broadcast), α=11.5 %. The corresponding peak-to-average power ratio is about 7 dB for 99.99 % of the time.

Theoretically, the difference of the peak-to-average power ratio between a multicarrier system and a single carrier system is a function of the number of carriers as:

$$\Delta(dB) = 10\log_{10} N$$

where N is the number of carriers. When N=1000, the difference could be 30 dB. However, this theoretical value can rarely occur. Since the input data is well scrambled, the chances of reaching its maximum value are very low, especially when the signal constellation size is large.

Since COFDM signal can be treated as a series of independent and identically distributed carriers, the central limiting theorem implies that the COFDM signal distribution should tend to be Gaussian when the number of carriers, N, is large. Generally, when N>20, which is the case for most of the OFDM systems, the distribution is very close to Gaussian. Its probability of above three times (9.6 dB peak-to-average ratio) of its variance, or average power, is about 0.1 %. For four times of variance, or 12 dB peak-to-average power ratio, it is less than 0.01 %.

It should be pointed out that, for each COFDM subchannel, there is usually no pulse shaping implemented. The peak-to-average power ratio for each subchannel depends only on the signal constellation.

In common practice, signals could be clipped because of limited quantization levels, rounding and truncation during the FFT computation as well as other distribution parameters after D/A conversion. It is safe to say that the Gaussian model can be used as the upper bound for the COFDM signals.

Nonlinear distortion

Since a broadcast transmitter is a nonlinear device, clipping will always happen for COFDM signal. However, clipping of a COFDM signal is similar to the impulse interference on which COFDM systems have strong immunity. Tests show that when clipping occurs at 0.1% of the time, the BER degradation is only 0.1-0.2 dB. Even at 1% of clipping, the degradation is 0.5-0.6 dB. However, the BER performance of COFDM system under nonlinear distortion might not be the decisive factor. When clipping occurs, energy would spill into the adjacent channels. More studies are required in this area. It has been reported that, for an OFDM system, a 9 dB output back-off causes negligible BER degradation and adjacent channel interference. Another study indicated that, for modern solid-state transmitters, a prudent back-off level would be around 6 dB.

VI Conclusions

OFDM/COFDM has long been studied and implemented to combat transmission channel impairments. Its applications have been extended from high frequency radio communications to telephone networks, digital audio broadcasting and terrestrial broadcasting of digital television. The advantages of COFDM, especially in the multipath propagation, interference and fading environment, make the technology a promising alternative in digital communications including mobile multimedia.
The advantages of OFDM are:

- Efficient use of the available bandwidth since the subchannels are overlapping
- Spreading out the frequency fading over many symbols. This effectively randomizes the burst errors caused by the Rayleigh fading, so that instead of several adjacent symbols (in time on a

single-carrier) being completely destroyed, (many) symbols in parallel are only slightly distorted.
- The symbol period is increased and thus the sensitivity of the system to delay spread is reduced.

The disadvantages of the OFDM modulation are:

- OFDM signal is contaminated by non-linear distortion of transmitter power amplifier, because it is a combined amplitude-frequency modulation (it is necessary to maintain linearity)
- OFDM is very sensitive to carrier frequency offset caused by the jitter of carrier wave and Doppler effect caused by moving of the mobile terminal.
- At the receiver, it is very difficult to decide the starting time of the FFT symbol

Communications research and current development of COFDM around the world will certainly provide us with valuable findings in theory and implementation. Further studies should be conducted on the synchronization of OFDM signal, power demand, counter-measures against frequency offset, fading and multiple access.

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