Chapter 2
OFDM: Principles and Challenges

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2.1 Introduction

The nature of future wireless applications demands high data rates. Naturally dealing with ever-unpredictable wireless channel at high data rate communications is not an easy task. The idea of multi-carrier transmission has surfaced recently to be used for combating the hostility of wireless channel and providing high data rate communications. OFDM is a special form of multi-carrier transmission where all the subcarriers are orthogonal to each other. OFDM promises a high user data rate transmission capability at a reasonable complexity and precision.

At high data rates, the channel distortion to the data is very significant, and it is somewhat impossible to recover the transmitted data with a simple receiver. A very complex receiver structure is needed which makes use of computationally expensive equalization and channel estimation algorithms to correctly estimate the channel, so that the estimations can be used with the received data to recover the originally transmitted data. OFDM can drastically simplify the equalization problem by turning the frequency-selective channel into a flat channel. A simple one-tap equalizer is needed to estimate the channel and recover the data.

Future telecommunication systems must be spectrally efficient to support a number of high data rate users. OFDM uses the available spectrum very efficiently which is very useful for multimedia communications. For all of the above reasons, OFDM has already been accepted by many of the future generation systems [1].

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V. Tarokh (ed.), *New Directions in Wireless Communications Research*,
DOI 10.1007/978-1-4419-0673-1_2,

2.2 History and Development of OFDM

Although OFDM has only recently been gaining interest from telecommunications industry, it has a long history of existence. It is reported that OFDM-based systems were in existence during the Second World War. OFDM had been used by the US military in several high-frequency military systems such as KINEPLEX, ANDEFT, and KATHRYN [2]. KATHRYN used AN/GSC-10 variable rate data modem built for high-frequency radio. Up to 34 parallel low-rate channels using PSK modulation were generated by a frequency-multiplexed set of subchannels. Orthogonal frequency assignment was used with channel spacing of 82 Hz to provide guard time between successive signaling elements [3].

In December 1966, Robert W. Chang[1] outlined a theoretical way to transmit simultaneous data stream through linear band-limited channel without *inter-symbol interference* (ISI) and *inter-carrier interference* (ICI). Subsequently, he obtained the first US patent on OFDM in 1970 [4]. Around the same time, Saltzberg[2] performed an analysis of the performance of the OFDM system. Until this time, we needed a large number of subcarrier oscillators to perform parallel modulations and demodulations.

A major breakthrough in the history of OFDM came in 1971 when Weinstein and Ebert[3] used *discrete Fourier transform* (DFT) to perform baseband modulation and demodulation focusing on efficient processing. This eliminated the need for bank of subcarrier oscillators, thus paving the way for easier, more useful, and efficient implementation of the system.

All the proposals until this time used guard spaces in frequency domain and a raised cosine windowing in time domain to combat ISI and ICI. Another milestone for OFDM history was when Peled and Ruiz[4] introduced *cyclic prefix* (CP) or cyclic extension in 1980. This solved the problem of maintaining orthogonal characteristics of the transmitted signals at severe transmission conditions. The generic idea that they placed was to use cyclic extension of OFDM symbols instead of using empty guard spaces in frequency domain. This effectively turns the channel as performing cyclic convolution, which provides orthogonality over dispersive channels when CP is longer than the channel impulse response [2]. It is obvious that introducing CP causes loss of signal energy proportional to length of CP compared to symbol length, but, on the other hand, it facilitates a zero ICI advantage which pays off.

[1] Robert W. Chang, *Synthesis of Band-limited Orthogonal Signals for Multichannel Data Transmission*, The Bell Systems Technical Journal, December 1966.

[2] B. R. Saltzberg, *Performance of an Efficient Parallel Data Transmission System*, IEEE Transactions on Communications, COM-15 (6), pp. 805–811, December 1967.

[3] S. B. Weinstein, P. M. Ebert, *Data Transmission of Frequency Division Multiplexing Using the Discrete Frequency Transform*, IEEE Transactions on Communications, COM-19(5), pp. 623–634, October 1971.

[4] R. Peled, A. Ruiz, *Frequency Domain Data Transmission Using Reduced Computational Complexity Algorithms*, in Proceeding of the IEEE International Conference on Acoustics, Speech, and Signal Processing, ICASSP ’80, pp. 964–967, Denver, USA, 1980.

By this time, inclusion of FFT and CP in OFDM system and substantial advancements in *digital signal processing* (DSP) technology made it an important part of telecommunications landscape. In the 1990s, OFDM was exploited for wideband data communications over mobile radio FM channels, *high-bit-rate digital subscriber lines* (HDSL at 1.6 Mbps), *asymmetric digital subscriber lines* (ADSL up to 6Mbps), and *very-high-speed digital subscriber lines* (VDSL at 100 Mbps).

Digital audio broadcasting (DAB) was the first commercial use of OFDM technology. Development of DAB started in 1987. By 1992, DAB was proposed and the standard was formulated in 1994. DAB services came to reality in 1995 in the United Kingdom and Sweden. The development of *digital video broadcasting* (DVB) was started in 1993. DVB along with *high-definition television* (HDTV) terrestrial broadcasting standard was published in 1995. At the dawn of the 20th century, several *wireless local area network* (WLAN) standards adopted OFDM on their physical layers. Development of European WLAN standard HiperLAN started in 1995. HiperLAN/2 was defined in June 1999 which adopts OFDM in physical layer. IEEE 802.11a has also adopted OFDM in its PHY layer.

Perhaps of even greater importance is the emergence of this technology as an enabler for future *4th generations* (4G) wireless systems, such as IMT-A. These systems, expected to emerge by the year 2015, promise to at last deliver on the wireless Nirvana of anywhere, anytime, anything communications. OFDM promises to gain prominence in this arena; therefore, it is expected to become the technology of choice in most wireless links.

2.3 The Benefit of Using Multi-carrier Transmission

Time dispersion represents a distortion of the signal that is manifested by the spreading of the modulation symbols in the time domain, also known as delay spread, and this is reflected by the ISI phenomenon. This is also reflected in frequency domain, by the inverse proportionality relation between coherence bandwidth and delay spread, i.e., the higher the delay spread, the lower the coherence bandwidth, and therefore the higher the channel frequency selectivity. For broadband multimedia communications the coherence bandwidth of the channel is always smaller than the modulation bandwidth. Thus in such conditions, the frequency selectivity effect cannot be avoided, which has a random pattern at any given time. This fading occurs when the channel introduces time dispersion and the delay spread is larger than the symbol period. Frequency-selective fading is difficult to compensate because the fading characteristics are random and may not be easily predictable. When there is no dispersion and the delay spread is less than the symbol period, the fading will be flat, thereby affecting all frequencies in the signal equally. Practically flat fading is easily estimated and compensated with a simple equalization [5, 6].

A single-carrier system suffers from ISI problem when the data rate is very high. According to previous discussions, we have seen that with a symbol duration T_{sym}, ISI occurs when $\tau_{max} > T_{sym}$. Multichannel transmission has surfaced to solve this problem. The idea is to increase the symbol duration and thus reduce the effect of ISI. Reducing the effect of ISI yields an easier equalization, which in turn means simpler reception techniques.

Wireless multimedia solutions require up to tens of Mbps for a reasonable QoS. If we consider single-carrier high-speed wireless data transmission, we see that the delay spread at such high data rates will definitely be greater than the symbol duration even considering the best-case outdoor scenario. Now, if we divide the high data rate channel over a number of subcarriers, then we have larger symbol duration in the subcarriers and the delay spread is much smaller than the symbol duration.

Figure 2.1 describes this very issue. Assuming that we have available bandwidth B of 1 MHz in a single-carrier approach, we transmit the data at symbol duration of 1 µs. Consider a typical outdoor scenario where the maximum delay spread can be as high as 10 µs, so at the worst-case scenario, at least 10 consecutive symbols will be affected by ISI due to the delay spread.

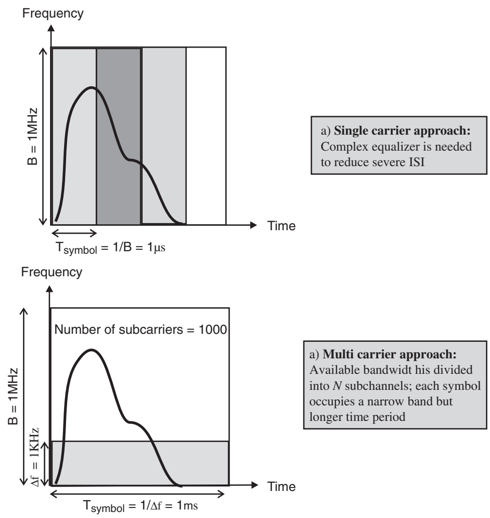

Fig. 2.1 Single carrier vs multi-carrier approach

In a single-carrier system, this situation is compensated by using equalization techniques. Using the estimates of channel impulse response, the equalizer multiplies complex conjugate of the estimated impulse response with the received data signal at the receiver. There are other well-known equalization algorithms available in the literature, such as adaptive equalization via LMS, RLS algorithms [7]. However, there are some practical computational difficulties in performing these equalization techniques at tens of Mbps with compact and low-cost hardware. It is worth mentioning here that compact and low-cost hardware devices do not necessarily function at very high data speed. In fact, equalization procedures take bulk of receiver resources, costing high computation power and thus overall service and hardware cost becomes high.

One way to achieve reasonable quality and solve the problems described above for broadband mobile communication is to use parallel transmission. In a crude sense, someone can say in principle that parallel transmission is just the summation of a number of single-carrier transmissions at the adjacent frequencies [8]. The difference is that the channels have lower data transmission rate than the original single-carrier system and the low rate streams are orthogonal to each other. If we consider a multi-carrier approach where we have N number of subcarriers, we can see that we can have $\frac{B}{N}$ Hz of bandwidth per sub-carrier. If $N = 1000$ and $B = 1\,\text{MHz}$, then we have a subcarrier bandwidth Δf of 1 kHz. Thus, the symbol duration in a subcarrier will be increased to 1 ms ($= \frac{1}{1\,\text{kHz}}$). Here each symbol occupies a narrowband but a longer time period. This clearly shows that the delay spread of 1 ms will not have any ISI effect on the received symbols in the outdoor scenario mentioned above. So, we can say that the multi-carrier approach turns the channel to a flat fading channel and thus can easily be estimated.

Theoretically increasing the number of subcarriers should be able to give better performance in a sense that we will be able to handle larger delay spreads. But several typical implementation problems arise with a large number of subcarriers. When we have large numbers of subcarriers, we have to assign the subcarrier frequencies very close to each other, if the available bandwidth is not increased. We know that the receiver needs to synchronize itself to the carrier frequency very well, otherwise a comparatively small carrier frequency offset may cause a large frequency mismatch between neighboring subcarriers. When the subcarrier spacing is very small, the receiver synchronization components need to be very accurate, which is still not possible with low-cost RF hardware. Thus, a reasonable trade-off between the subcarrier spacing and the number of subcarriers must be achieved.

Table 2.1 describes how multi-carrier approach can convert the channel to flat fading channel from frequency-selective fading channel. We have considered a

Table 2.1 Comparison of single-carrier and multi-carrier approach in terms of channel frequency selectivity

Design parameters for outdoor channel	Required data rate	1 Mbps
	RMS delay spread, τ_{rms}	$10\,\mu\text{s}$
	Channel coherence bandwidth, $B_c = \frac{1}{5\tau_{rms}}$	20 kHz
	Frequency selectivity condition	$\sigma > \frac{T_{sym}}{10}$
Single-carrier approach	Symbol duration, T_{sym}	$1\,\mu\text{s}$
	Frequency selectivity	$10\,\mu\text{s} > \frac{1\,\mu s}{10} \Longrightarrow$ **YES**
	ISI occurs as the channel is frequency selective	
Multi-carrier approach	Total number of subcarriers	128
	Data rate per subcarrier	7.8125 kbps
	Symbol duration per subcarrier	$T_{carr} = 128\,\mu s$
	Frequency selectivity	$10\,\mu s > \frac{128\,\mu s}{10} \Longrightarrow$ **NO**
	ISI is reduced as flat fading occurs. CP completely removes the remaining ISI; and also inter-block interference is removed	

multi-carrier system with respect to a single-carrier system, where the system data rate requirement is 1 Mbps. When we use 128 subcarriers for multi-carrier system, we can see that the ISI problem is clearly solved. It is obvious that if we increase the number of subcarriers, the system will theoretically provide even better performance.

2.4 OFDM Transceiver Systems

A complete OFDM transceiver system is described in Fig. 2.2. In this model, *forward error control/correction* (FEC) coding and interleaving are added in the system to obtain the robustness needed to protect against burst errors. An OFDM system with addition of channel coding and interleaving is referred to as *coded OFDM* (COFDM).

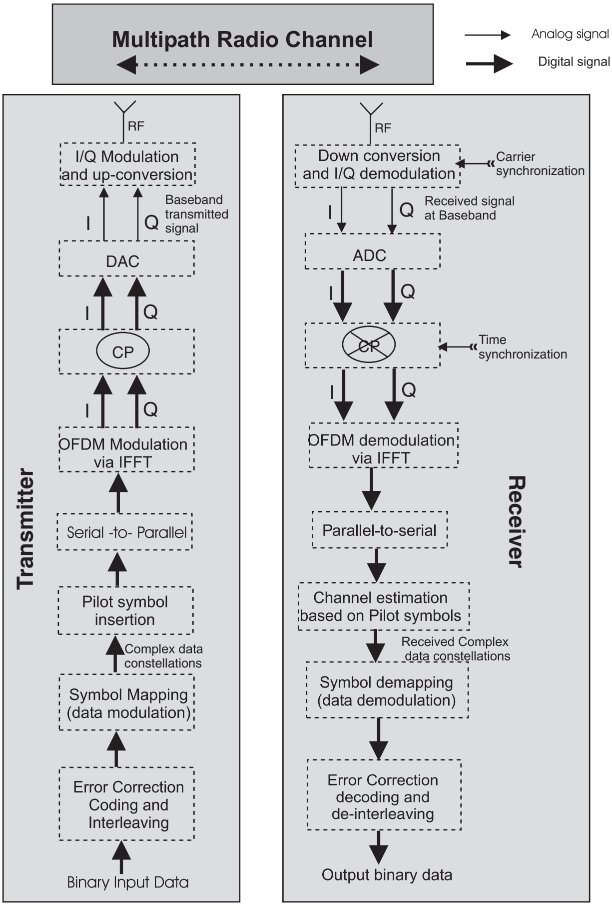

Fig. 2.2 OFDM transceiver model

In a digital domain, binary input data are collected and FEC coded with schemes such as convolutional codes. The coded bit stream is interleaved to obtain diversity gain. Afterward, a group of channel-coded bits are gathered together (1 for BPSK, 2 for QPSK, 4 for 16-QAM, etc.) and mapped to corresponding constellation points. At this point, the data are represented as complex numbers and they are in serial. Known pilot symbols mapped with known mapping schemes can be inserted at this moment. A serial to parallel converter is applied and the IFFT operation is performed on the parallel complex data. The transformed data are grouped together again, as per the number of required transmission subcarriers. Cyclic prefix is inserted in every block of data according to the system specification and the data are multiplexed in a serial fashion. At this point of time, the data are OFDM modulated and ready to be transmitted. A *digital-to-analog converter* (DAC) is used to transform the time-domain digital data to time-domain analog data. RF modulation is performed and the signal is up-converted to transmission frequency.

After the transmission of OFDM signal from the transmitter antenna, the signals go through all the anomaly and hostility of wireless channel. After receiving the signal, the receiver down-converts the signal and converts to digital domain using *analog-to-digital converter* (ADC). At the time of down-conversion of received signal, carrier frequency synchronization is performed. After ADC conversion, symbol timing synchronization is achieved. An FFT block is used to demodulate the OFDM signal. After that, channel estimation is performed using the demodulated pilots. Using the estimations, the complex received data are obtained which are demapped according to the transmission constellation diagram. At this moment, FEC decoding and de-interleaving are used to recover the originally transmitted bit stream.

2.5 Analytical Model of OFDM System

In this section, an analytical time-domain model of an OFDM transmitter and receiver, as well as a channel model, is derived.

2.5.1 Transmitter

The sth OFDM symbol is found using the sth subcarrier block, $\mathbf{X}_s[k]$. In practice, the OFDM signal is generated using an inverse DFT. In the following model, the transmitter is assumed to be ideal, i.e., sampling or filtering do not affect the signal at the transmitter side. Therefore, a continuous transmitter output signal may be constructed directly using a Fourier series representation within each OFDM symbol interval.

Each OFDM symbol contains N subcarriers, where N is an even number (frequently a power of 2). The OFDM symbol duration is T_u seconds, which must be a whole number of periods for each subcarrier. Defining the subcarrier spacing as $\Delta\omega$, the shortest duration that meets this requirement is written as

$$T_u = \frac{2\pi}{\Delta\omega} \Leftrightarrow \Delta\omega = \frac{2\pi}{T_u} = 2\pi\Delta f. \tag{2.1}$$

Using this relation, the spectrum of the Fourier series for the duration of the sth OFDM symbol is written as

$$\mathbf{X}_s(\omega) = \sum_{k=-N/2}^{N/2-1} \mathbf{X}_s[k]\delta_c(\omega - k\Delta\omega). \tag{2.2}$$

In order to provide the OFDM symbol in the time domain, the spectrum in (2.2) is inverse Fourier transformed and limited to a time interval of T_u. The time-domain signal, $\tilde{x}_s(t)$, is therefore written as

$$\begin{aligned} \tilde{x}_s(t) &= \mathcal{F}\{\mathbf{X}_s(\omega)\}\, \Xi_{T_u}(t) \\ &= \begin{cases} \frac{1}{\sqrt{T_u}} \sum_{k=-N/2}^{N/2-1} \mathbf{X}_s[k] e^{j\Delta\omega k t} & 0 \le t < T_u, \\ 0 & \text{otherwise} \end{cases} \end{aligned} \tag{2.3}$$

(2.4)

where Ξ_{T_u} is a unity amplitude rectangular gate pulse of duration T_u. Following the frequency- to time-domain conversion, the signal is extended, and the cyclic prefix is added:

$$\tilde{x}_s'(t) = \begin{cases} \tilde{x}_s(t + T_u - T_g) & 0 \le t < T_g \\ \tilde{x}_s(t - T_g) & T_g < t < T_s \\ 0 & \text{otherwise} \end{cases}, \tag{2.5}$$

where T_g is the cyclic prefix duration and $T_s = T_u + T_g$ is the total OFDM symbol duration. It should be noted that (2.5) has the following property:

$$\tilde{x}_s'(t) = \tilde{x}_s'(t + T_u) \Leftrightarrow 0 \le t < T_g, \tag{2.6}$$

that is, a periodicity property within the interval [0, T_g]. The transmitted complex baseband signal, $\tilde{s}(t)$, is formed by concatenating all OFDM symbols in the time domain:

$$\tilde{s}(t) = \sum_{s=0}^{S-1} \tilde{x}_s'(t - sT_s). \tag{2.7}$$

This signal is finally upconverted to a carrier frequency and transmitted:

$$s(t) = \Re e\left\{\tilde{s}(t)e^{j2\pi f_c t}\right\}, \tag{2.8}$$

where $s(t)$ denotes the transmitted RF signal and f_c is the RF carrier frequency. For frequency hopping systems, the carrier frequency is changed at certain intervals. This is written as

$$f_c[s] = f_{c,0} + f_h[s], \tag{2.9}$$

where $f_c[s]$ is the carrier frequency for the sth OFDM symbol, $f_{c,0}$ is the center frequency of the band, and $f_h[s]$ is the frequency deviation from the band center when transmitting the sth OFDM symbol. The period of $f_h[s]$ is χ, where χ is the hopping sequence period measured in whole OFDM symbols.

The transmitter model described in this section is illustrated in Fig. 2.3.

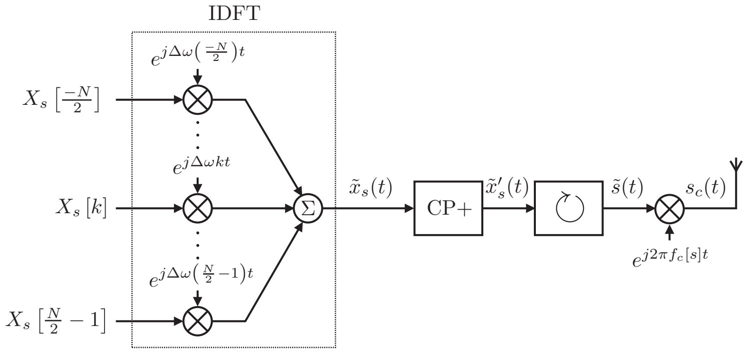

Fig. 2.3 Transmitter diagram for the OFDM analytical model given by (2.1)–(2.9). The subcarriers for the sth OFDM symbol each modulates a carrier; the carriers are separated by $\Delta\omega$. The resulting waveforms are then summed, and the CP is added. The symbol ⟳ represents the concatenation of the OFDM symbols given by (2.7). The resulting signal is then up-converted to a carrier frequency and transmitted

2.5.2 Channel

The channel is modeled as a time-domain complex-baseband transfer function, which may then be convolved with the transmitted signal to determine the signal at the receiver side. The channel baseband equivalent impulse response function for the uth user, $\tilde{h}_u(t)$ is defined as

$$\tilde{h}_u(\tau, t) = \sum_{l=0}^{L} h_{u,l}(t)\delta_c(\tau - \tau_l), \tag{2.10}$$

where $h_{u,l}(t)$ is the complex gain of the lth multipath component for the uth user at time t. The channel is assumed to be static for the duration of one OFDM symbol, and the path gain coefficients for each path contribution are assumed to be uncorrelated. No assumption is made for the autocorrelation properties of each path, except in the case of frequency hopping systems. In such systems, the channel is assumed to be completely uncorrelated between two frequency hops, provided that the distance in frequency is sufficiently large.

As the channel is assumed to be static over each OFDM symbol, (2.10) is redefined as

$$\tilde{h}_{u,s}(t) = \sum_{l=0}^{L} h_{u,l}[s]\delta_c(t - \tau_l), \tag{2.11}$$

where

$$h_{u,l}[s] = h_{u,l}(t), \qquad sT_s \leq t < (s+1)T_s.$$

The corresponding frequency-domain channel transfer function, $H_{u,s}$, can then be found using Fourier transformation:

$$\begin{aligned} H_{u,s}(\omega) &= \mathcal{F}\left\{\tilde{h}_{u,s}(t)\right\} \\ &= \int_{-\infty}^{\infty} \tilde{h}_{u,s}(t)e^{j\omega t}dt. \end{aligned} \tag{2.12}$$

The time-domain channel model is illustrated in Fig. 2.4.

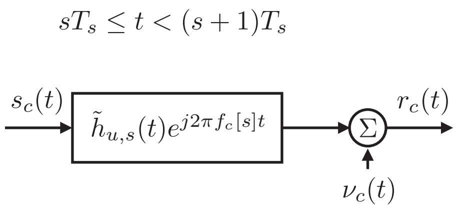

Fig. 2.4 A diagram of the channel model given by (2.10)–(2.11). The transmitted signal passes through the channel, and noise is added

2.5.3 Receiver

The signal at the receiver side consists of multiple echoes of the transmitted signal, as well as thermal (white gaussian) noise and interference. The RF signal received by the uth user is written as

$$r(t) = \Re e\left\{(\tilde{s}(t) * \tilde{h}_{u,s}(t))e^{j2\pi f_c[s]t}\right\} + \nu(t), \qquad sT_s \leq t < (s+1)T_s, \tag{2.13}$$

where $\nu(t)$ is a real-valued, passband signal combining additive noise and interference. The receiver now has to recreate the transmitted signal. Aside from noise and multipath effects, other imperfections in the receiver may also affect this process:

- **Timing error**: In order to demodulate the signal, the receiver must establish the correct timing. This means that the receiver must estimate which time instant corresponds to $t = 0$ in the received signal (as seen from the transmitted signal point of view). As there are different uncertainties involved, a timing error of δt is assumed.

- **Frequency error**: Similarly, the local oscillator of the receiver may oscillate at an angular frequency that is different from the angular frequency of the incoming signal. This difference is denoted as $\delta\omega = 2\pi\delta f$.

The shifted timescale in the receiver is denoted as $t' = t - \delta t$. Furthermore, due to the angular frequency error $\delta\omega$, the down-converted signal spectrum is shifted in frequency. The down-converted signal is therefore written as

$$\tilde{r}(t) = (\tilde{s}(t') * \tilde{h}_{u,s}(t))e^{j\delta\omega t} + \tilde{\nu}(t'), \qquad sT_s \leq t < (s+1)T_s, \tag{2.14}$$

where $\tilde{\nu}(t)$ is the complex envelope of the down-converted AWGN. The signal is divided into blocks each T_s-long, and the CP is removed from each of them. The sth received OFDM symbol block, $y'_s(t)$ is defined as

$$\tilde{y}'_s(t) = \tilde{r}(t' - sT_s), \qquad 0 \leq t < T_s. \tag{2.15}$$

The signal block corresponding to $\tilde{x}_s(t)$, $\tilde{y}_s(t)$ is found by removing the CP from each $\tilde{y}'_s(t)$:

$$\tilde{y}_s(t) = \tilde{y}'_s(t + T_g), \qquad 0 \leq t < T_s - T_g, \tag{2.16}$$

which can be rewritten as

$$\begin{aligned}
\tilde{y}_s(t) &= \tilde{y}'_s(t + T_g), \qquad 0 \leq t \leq T_u \\
&= \tilde{r}(t' + T_g - sT_s) \\
&= (\tilde{s}(t' + T_g - sT_s) * \tilde{h}_{u,s}(t))e^{j\delta\omega t} + \tilde{\nu}(t' + T_g - sT_s) \\
&= (\tilde{x}'_s(t' + T_g) * \tilde{h}_{u,s}(t))e^{j\delta\omega t} + \tilde{\nu}_s(t') \\
&= (\tilde{x}_s(t') * \tilde{h}_{u,s}(t))e^{j\delta\omega t} + \tilde{\nu}_s(t'),
\end{aligned} \tag{2.17}$$

where $\tilde{\nu}_s(t')$ is the noise signal block of duration T_u corresponding to the sth OFDM symbol.

In order to recreate the transmitted subcarriers, N correlators are used, each one correlating the incoming signal with the kth subcarrier frequency over an OFDM symbol period:

$$Y_s[k] = \frac{1}{\sqrt{T_u}} \int_0^{T_u} \tilde{y}_s(t')e^{j\Delta\omega kt} dt. \tag{2.18}$$

In order to determine the correlator output, (2.18) may be seen as taking the continuous Fourier transform of (2.17) multiplied by the rectangular pulse $\Xi_{T_u}(t)$ and evaluating it at the corresponding subcarrier frequency. Assuming that the timing error is low enough to avoid ISI

$$0 \leq \delta t < T_g - \max(\tau_l)$$

the continuous Fourier transform can be written as

$$\begin{aligned}
Y_s(\omega) &= \mathcal{F}\left\{\tilde{y}_s(t)\Xi_{T_u}(t)\right\} \\
&= \mathcal{F}\left\{(\tilde{x}_s(t') * \tilde{h}_{u,s}(t))e^{j\delta\omega t} + \tilde{\nu}_s(t')\right\} * T_u e^{j\pi\frac{\omega}{\Delta\omega}}\mathrm{sinc}\left(\frac{\omega}{\Delta\omega}\right) \\
&= \mathcal{F}\left\{(\tilde{x}_s(t') * \tilde{h}_{u,s}(t))e^{j\delta\omega t}\right\} * T_u e^{j\pi\frac{\omega}{\Delta\omega}}\mathrm{sinc}\left(\frac{\omega}{\Delta\omega}\right) + N_s(\omega) \\
&= \mathcal{F}\left\{\tilde{x}_s(t') * \tilde{h}_{u,s}(t)\right\} * \delta_c(\omega-\delta\omega) * T_u e^{j\pi\frac{\omega}{\Delta\omega}}\mathrm{sinc}\left(\frac{\omega}{\Delta\omega}\right) + N_s(\omega) \\
&= e^{-j\omega\delta t}\mathcal{F}\left\{\tilde{x}_s(t) * \tilde{h}_{u,s}(t)\right\} * \delta_c(\omega-\delta\omega) * T_u e^{j\pi\frac{\omega}{\Delta\omega}}\mathrm{sinc}\left(\frac{\omega}{\Delta\omega}\right) + N_s(\omega) \\
&= e^{-j\omega(\delta t+\frac{\pi}{\Delta\omega})}\sum_{k'=N/2}^{N/2-1}\mathbf{X}_s[k']H_{u,s}(k'\Delta\omega)\mathrm{sinc}\left(\frac{\omega-k'\Delta\omega-\delta\omega}{\Delta\omega}\right) + N_s(\omega),
\end{aligned} \tag{2.19}$$

where

$$N_s(\omega) = \mathcal{F}\left\{\tilde{\nu}_s(t')\right\} * T_u e^{j\pi\frac{\omega}{\Delta\omega}}\mathrm{sinc}\left(\frac{\omega}{\Delta\omega}\right) \tag{2.20}$$

is the Fourier transform of the AWGN contribution. The correlator output at the kth correlator is then found as

$$\begin{aligned}
Y_s[k] &= Y_s(k\Delta\omega) \\
&= e^{-jk\Delta\omega(\delta t+\frac{\pi}{\Delta\omega})}\sum_{k'=N/2}^{N/2-1}\mathbf{X}_s[k']H_{u,s}(k'\Delta\omega)\mathrm{sinc}\left(\frac{k\Delta\omega-k'\Delta\omega-\delta\omega}{\Delta\omega}\right) \\
&\quad + N_s(k\Delta\omega).
\end{aligned} \tag{2.21}$$

For zero frequency error, (2.21) reduces to

$$Y_s[k] = e^{-jk\Delta\omega(\delta t+\frac{\pi}{\Delta\omega})}\mathbf{X}_s[k]H_{u,s}[k] + N_s[k], \quad \delta\omega = 0, \tag{2.22}$$

where

$$N_s[k] = N_s(k\Delta\omega), \tag{2.23}$$

$$H_{u,s}[k] = H_{u,s}(k\Delta\omega). \tag{2.24}$$

From (2.21), it is seen that the kth correlator output, $Y_s[k]$, corresponds to the transmitted subcarrier, $\mathbf{X}_s[k]$, with AWGN, ICI, and a complex gain term (amplitude and phase shift) due to imperfect timing and channel effects. The analytical model for the receiver is illustrated in Fig. 2.5.

When estimating the channel, the constant phase rotation term and the channel transfer function would be estimated jointly (as the receiver cannot discern between the two). In the following, the timing delay phase shift is omitted for clarity. Defining the equalization factor for the kth subcarrier of the sth OFDM symbol and uth user as $Z_{u,s}[k]$, the subcarrier estimate is written as

$$\begin{aligned}\hat{X}_s[k] &= Z_{u,s}\,[k]\,Y_s[k] \\ &= Z_{u,s}\,[k]\,H_{u,s}\,[k]\,\mathbf{X}_s[k] + Z_{u,s}\,[k]\,N_s[k].\end{aligned} \tag{2.25}$$

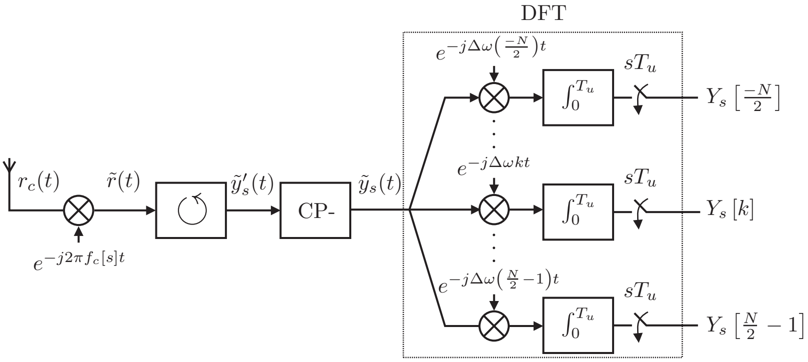

Fig. 2.5 Receiver diagram for the OFDM analytical model, given by (2.13)–(2.22). The received signal (suffering from multipath effects and AWGN) is converted down to baseband. The symbol ↻ represents the division of the received signal into blocks, given by (2.15). The CP is removed from each block, and the signal is then correlated with each subcarrier frequency, as shown by (2.18)

Assuming a zero-forcing, frequency-domain equalizer (as well as perfect channel estimation and zero frequency error), the corresponding equalizer gain is written as

$$Z_{u,s}\,[k] = \frac{1}{H_{u,s}\,[k]}$$

and (2.25) is rewritten as

$$\hat{X}_s[k] = \mathbf{X}_s[k] + \frac{N_s[k]}{H_{u,s}\,[k]}. \tag{2.26}$$

It is observed that although this is an unbiased estimator for $\mathbf{X}_s[k]$, the signal-to-noise ratio decreases drastically for subcarriers in deep fades.

2.5.4 Sampling

Although the receiver may be modeled in the continuous time domain, an OFDM receiver uses discrete signal processing to obtain the estimate of the transmitted subcarriers.

When the received signal is modeled as a Dirac impulse train, i.e., an ideally sampled signal, (2.17) is instead written as

$$\tilde{y}_{s,d}(t) = \sum_{n=0}^{N-1} \tilde{y}_s[n]\delta_c(t - nT), \tag{2.27}$$

where

$$T = \frac{T_u}{N} \tag{2.28}$$

is the sample duration and

$$\tilde{y}_s[n] = \tilde{y}_s(nT), \quad n \in \{0, 1, ..., N-1\} \tag{2.29}$$

is the discrete sequence corresponding to the sampled values of $\tilde{y}_s(t)$. When (2.27) is inserted into (2.18), the correlation becomes the discrete Fourier transform of the received signal. It can be shown, however, that (2.21)–(2.26) are still valid in the discrete-time case.

2.6 Advantages of OFDM System

2.6.1 Combating ISI and Reducing ICI

When signal passes through a time-dispersive channel, the orthogonality of the signal can be jeopardized. CP helps to maintain orthogonality between the sub-carriers. Before CP was invented, guard interval was proposed as the solution. Guard interval was defined by an empty space between two OFDM symbols, which serves as a buffer for the multipath reflection. The interval must be chosen as larger than the expected maximum delay spread, such that multipath reflection from one symbol would not interfere with another. In practice, the empty guard time introduces ICI, which is crosstalk between different subcarriers, meaning they are no longer orthogonal to each other [2]. A better solution was later found, that is, cyclic extension of OFDM symbol or CP, which is a copy of the last part of OFDM symbol, appended in front of the transmitted OFDM symbol [9] (see Fig. 2.6).

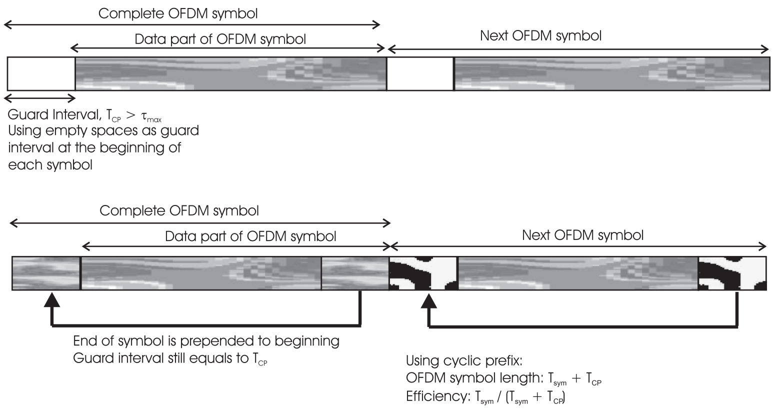

Fig. 2.6 Definition of cyclic prefix as the guard interval in OFDM systems

CP still occupies the same time interval as guard period, but it ensures that the delayed replicas of the OFDM symbols will always have a complete symbol within the FFT interval (often referred as FFT window); this makes the transmitted signal periodic. This periodicity plays a very significant role as this helps maintaining the orthogonality. The concept of being able to do this, and what it means, comes from the nature of IFFT/FFT process. When the IFFT is taken for a symbol period during OFDM modulation, the resulting time sample process is technically periodic. In a Fourier transform, all the resultant components of the original signal are orthogonal to each other. So, in short, by providing periodicity to the OFDM source signal, CP makes sure that subsequent subcarriers are orthogonal to each other.

At the receiver side, CP is removed before any processing starts. As long as the length of CP interval is larger than maximum expected delay spread τ_{max}, all reflections of previous symbols are removed and orthogonality is restored. The orthogonality is lost when the delay spread is larger than the length of CP interval. Inserting CP has its own cost, indeed we loose a part of signal energy since it carries no information. The loss is measured as

$$SNR_{loss\_CP} = -10\log_{10}\left(1 - \frac{T_{CP}}{T_{sym}}\right). \tag{2.30}$$

Here, T_{CP} is the interval length of CP and T_{sym} is the OFDM symbol duration. It is understood that although we loose part of signal energy, the fact that we get zero ICI and ISI situation pay off the loss.

To conclude, CP gives twofold advantages, first occupying the guard interval, it removes the effect of ISI and by maintaining orthogonality it completely removes the ICI. The cost in terms of signal energy loss is not too significant.

2.6.2 Spectral Efficiency

Figure 2.7 illustrates the difference between conventional FDM and OFDM systems, where for $SC\ BW$ one means subcarrier bandwidth. In the case of OFDM, a better spectral efficiency is achieved by maintaining orthogonality between the subcarriers. When orthogonality is maintained between different subchannels during transmission, then it is possible to separate the signals very easily at the receiver side. Classical FDM ensures this by inserting guard bands between subchannels. These guard bands keep the subchannels far enough so that separation of different subchannels is possible. Naturally inserting guard bands results in inefficient use of spectral resources.

Orthogonality makes it possible in OFDM to arrange the subcarriers in such a way that the sidebands of the individual carriers overlap and still the signals are received at the receiver without being interfered by ICI. The receiver acts as a bank of demodulators, translating each subcarrier down to DC, with the resulting signal integrated over a symbol period to recover raw data. If the other subcarriers are all down-converted to the frequencies that, in the time domain, have a whole number

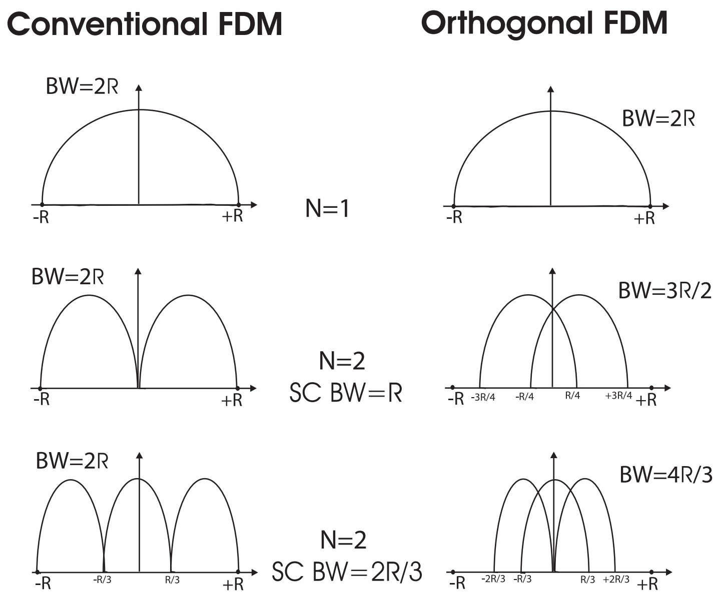

Fig. 2.7 Spectrum efficiency of OFDM compared to conventional FDM

of cycles in a symbol period T_{sym}, then the integration process results in zero contribution from all other carriers. Thus, the subcarriers are linearly independent (i.e., orthogonal) if the carrier spacing is a multiple of $\frac{1}{T_{sym}}$ [10].

2.6.3 Some Other Benefits of OFDM System

1. The beauty of OFDM lies in its simplicity. One trick of the trade that makes OFDM transmitters low cost is the ability to implement the mapping of bits to unique carriers via the use of IFFT [11].
2. Unlike CDMA, OFDM receiver collects signal energy in frequency domain, thus it is able to protect energy loss at frequency domain.
3. In a relatively slow time-varying channel, it is possible to significantly enhance the capacity by adapting the data rate per subcarrier according to SNR of that particular subcarrier [2].
4. OFDM is more resistant to frequency-selective fading than single-carrier systems.
5. The OFDM transmitter simplifies the channel effect, thus a simpler receiver structure is enough for recovering transmitted data. If we use coherent modulation schemes, then very simple channel estimation (and/or equalization) is needed, on the other hand, we need no channel estimator if differential modulation schemes are used.

6. The orthogonality preservation procedures in OFDM are much simpler compared to CDMA or TDMA techniques even in very severe multipath conditions.
7. It is possible to use maximum likelihood detection with reasonable complexity [12].
8. OFDM can be used for high-speed multimedia applications with low service cost.
9. OFDM can support dynamic packet access.
10. Single-frequency networks are possible in OFDM, which is especially attractive for broadcast applications.
11. Smart antennas can be integrated with OFDM. MIMO systems and space–time coding can be realized on OFDM and all the benefits of MIMO systems can be obtained easily. Adaptive modulation and tone/power allocation are also realizable on OFDM.

2.7 Disadvantages of OFDM System

2.7.1 Strict Synchronization Requirement

OFDM is highly sensitive to time and frequency synchronization errors, and especially at frequency synchronization errors, everything can go wrong [13]. Indeed, demodulation of an OFDM signal with an offset in the frequency can lead to a high bit error rate.

The source of frequency synchronization errors is two: first one being the difference between local oscillator frequencies in transmitter and receiver, second being relative motion between the transmitter and receiver that gives Doppler spread. Local oscillator frequencies at both transmitter and receiver must match as closely as they can. For higher number of subchannels, the matching should be even better. Motion of transmitter and receiver causes the other frequency error. So, OFDM may show significant performance degradation at high-speed moving vehicles [4].

To optimize the performance of an OFDM link, accurate synchronization is of prime importance. Synchronization needs to be done in three factors: symbol, carrier frequency, and sampling frequency synchronization. A good description of synchronization procedures is given in [14].

2.7.2 Peak-to-Average Power Ratio (PAPR)

Peak-to-average power ratio (PAPR) is proportional to the number of subcarriers used for OFDM systems. An OFDM system with large number of subcarriers will thus have a very large PAPR when the subcarriers add up coherently. Large PAPR of a system makes the implementation of digital-to-analog converter (DAC) and analog-to-digital converter (ADC) extremely difficult. The design of RF amplifier also becomes increasingly difficult as the PAPR increases.

The *clipping and windowing* technique reduces PAPR by non-linear distortion of the OFDM signal. It thus introduces self-interference as the maximum amplitude level is limited to a fixed level. It also increases the out-of-band radiation, but this is the simplest method to reduce the PAPR. To reduce the error rate, additional forward error correcting codes can be used in conjunction with the clipping and windowing method.

Another technique called *linear peak cancelation* can also be used to reduce the PAPR. In this method, time-shifted and time-scaled reference function is subtracted from the signal, such that each subtracted reference function reduces the peak power of at least one signal sample. By selecting an appropriate reference function with approximately the same bandwidth as the transmitted function, it can be assured that the peak power reduction does not cause out-of-band interference. One example of a suitable reference function is a *raised cosine window*. Detailed discussion about coding methods to reduce PAPR can be found in [2].

2.7.3 Co-channel Interference in Cellular OFDM

In cellular communication systems, CCI is combated by combining adaptive antenna techniques, such as sectorization, directive antenna, antenna arrays. Using OFDM in cellular systems will give rise to CCI. Similarly with the traditional techniques, with the aid of beam steering, it is possible to focus the base station's antenna beam on the served user, while attenuating the co-channel interferers.

2.8 OFDM System Design Issues

System design always needs a complete and comprehensive understanding and consideration of critical parameters. OFDM system design is of no exception, as it deals with some critical, and often conflicting parameters. Basic OFDM philosophy is to decrease data rate at the subcarriers, so that the symbol duration increases, thus the multipaths are effectively removed. This poses a challenging problem, as higher value for CP interval will give better result, but it will increase the loss of energy due to insertion of CP. Thus, a trade-off must be obtained for a reasonable design.

2.8.1 OFDM System Design Requirements

OFDM systems depend on four system requirements:

- **Available bandwidth:** Bandwidth is always the scarce resource, so the mother of the system design should be the available bandwidth for operation. The amount of bandwidth will play a significant role in determining number of subcarriers, because with a large bandwidth, we can easily fit in a large number of subcarriers with reasonable guard space.

- **Required bit rate:** The overall system should be able to support the data rate required by the users. For example, to support broadband wireless multimedia communication, the system should operate at more than 10 Mbps at least.
- **Tolerable delay spread:** Tolerable delay spread will depend on the user environment. Measurements show that indoor environment experiences maximum delay spread of few hundreds of ns at most, whereas outdoor environment can experience up to $10\,\mu s$. So the length of CP should be determined according to the tolerable delay spread.
- **Doppler values:** Users on a high-speed vehicle will experience higher Doppler shift, whereas pedestrians will experience smaller Doppler shift. These considerations must be taken into account.

2.8.2 OFDM System Design Parameters

The design parameters are derived according to the system requirements. Following are the design parameters for an OFDM system [2]:

- **Number of subcarriers:** Increasing number of subcarriers will reduce the data rate via each subcarrier, which will make sure that the relative amount of dispersion in time caused by multipath delay will be decreased (see Fig. 2.8). But when there are large numbers of subcarriers, the synchronization at the receiver side will be extremely difficult.
- **Guard time (CP interval) and symbol duration:** A good ratio between the CP interval and symbol duration should be found, so that all multipaths are resolved and not significant amount of energy is lost due to CP (see Fig. 2.9). As a thumb rule, the CP interval must be two to four times larger than the *root mean square* (RMS) delay spread. Symbol duration should be much larger than the guard time to minimize the loss of SNR, but within reasonable amount. It cannot be arbitrarily large, because larger symbol time means that more subcarriers can fit within the symbol time. More subcarriers increase the signal processing load at both the transmitter and receiver, increasing the cost and complexity of the resulting device [15].
- **Subcarrier spacing:** Subcarrier spacing must be kept at a level so that synchronization is achievable. This parameter will largely depend on available bandwidth and the required number of subchannels.
- **Modulation type per subcarrier:** This is trivial, because different modulation schemes will give different performances. Adaptive modulation and bit loading may be needed depending on the performance requirement. It is interesting to note that the performance of OFDM systems with differential modulation compares quite well with systems using non-differential and coherent demodulation

[16]. Furthermore, the computation complexity in the demodulation process is quite low for differential modulations.

- **FEC coding:** Choice of FEC code will play a vital role also. A suitable FEC coding will make sure that the channel is robust to all the random errors.

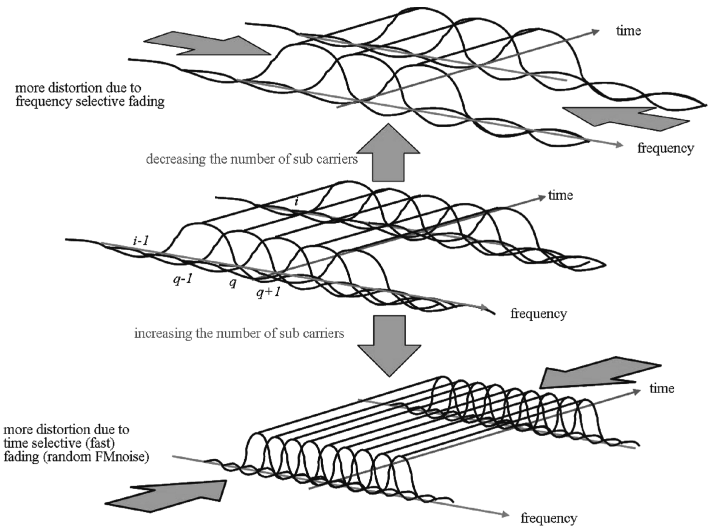

Fig. 2.8 Design of subcarrier spacing in OFDM systems

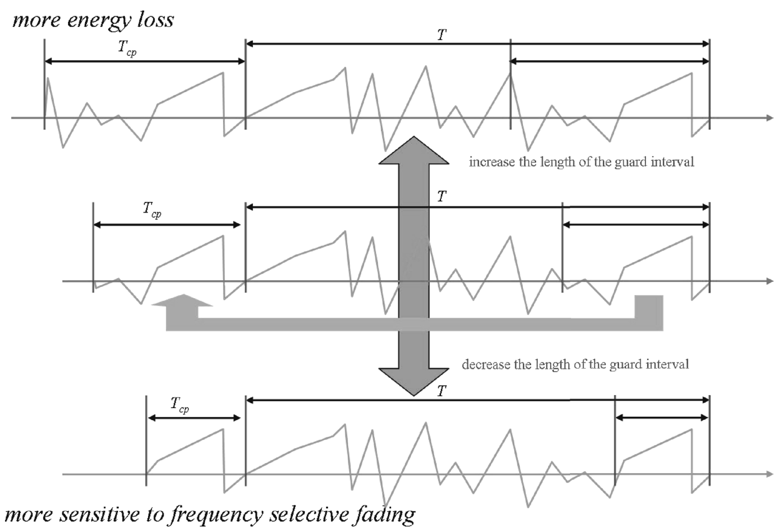

Fig. 2.9 Design of CP duration in OFDM systems

2.9 Multi-carrier Based Access Techniques

In this chapter, we present some of the main multiple access techniques that can be defined based on the original OFDM-type multi-carrier techniques.

2.9.1 Definition of Basic Schemes

It is imperative to understand the basic properties of three fundamental multi-carrier-based multiple access techniques, namely OFDMA, OFDM-TDMA, and OFDM-CDMA before embarking on studies related to probable access technique for 4G wireless communication systems, thus we here briefly summarize the basic properties of these three access schemes.

2.9.1.1 OFDM-TDMA

In OFDM-TDMA, a particular user is given all the subcarriers of the system for any specific OFDM symbol duration. Thus, the users are separated via time slots. All symbols allocated to all users are combined to form a OFDM-TDMA frame. The number of OFDM symbols per frame can be varied based on each user's requirement. Frequently, an error correcting code is applied to the data to compensate for the channel nulls experienced by several random bits. This scheme allows MS to reduce its power consumption, as the MS shall process only OFDM symbols which are dedicated to it. On the other hand, the data are sent to each user in bursts, thus degrading performance for delay-constrained systems [17].

Different OFDM symbols can be allocated to different users based on certain allocation conditions. Since the OFDM-TDMA concept allocates the whole band width to a single user, a reaction to different subcarrier attenuations could consist of leaving out highly distorted subcarriers [18]. The number of OFDM symbols per user in each frame can be adapted accordingly to support heterogeneous data rate requirements. An efficient multiple access scheme should grant a high flexibility when it comes to the allocation of time-bandwidth resources. On the one hand, the behavior of the frequency-selective radio channel should be taken into account, while on the other hand the user requirements for different and/or changing data rates have to be met [19]. For example, both for OFDMA and OFDM-TDMA, the usage of AMC on different subcarriers, as proposed in [20], may increase overall system throughput and help in further exploiting CSI.

2.9.1.2 OFDMA

In OFDMA, available subcarriers are distributed among all the users for transmission at any time instant. The subcarrier assignment is made for the user lifetime, or at least for a considerable time frame. The scheme was first proposed for CATV systems [21], and later adopted for wireless communication systems.

OFDMA can support a number of identical downstreams, or different user data rates [e.g., assigning a different number of subcarriers to each user]. Based on the subchannel condition, different baseband modulation schemes can be used for the individual subchannels, e.g., QPSK, 16-QAM, and 64-QAM. This is investigated in numerous papers and referred to as adaptive subcarrier, bit, and power allocation or QoS allocation [20, 22, 23, 24].

In OFDMA, frequency hopping, one form of spread spectrum, can be employed to provide security and resilience to inter-cell interference.

In OFDMA, the granularity of resource allocation is higher than that of OFDM-TDMA, i.e., the flexibility can be accomplished by suitably choosing the subcarriers associated with each user. Here, the fact that each user experiences a different radio channel can be exploited by allocating only "good" subcarriers with high SNR to each user. Furthermore, the number of subchannels for a specific user can be varied, according to the required data rate. Thus, multi-rate system can be achieved without increasing system complexity very much.

2.9.1.3 OFDM-CDMA

In OFDM-CDMA [25, 26], user data are spread over several subcarriers and/or OFDM symbols using spreading codes, and combined with signal from other users [27]. The idea of OFDM-CDMA can be attributed to several researchers working independently at almost the same time on hybrid access schemes combining the benefits of OFDM and CDMA. OFDM provides a simple method to overcome the ISI effect of the multipath frequency-selective wireless channel, while CDMA provides the frequency diversity and the multi-user access scheme. Different types of spreading codes have been investigated. Orthogonal codes are preferred in case of DL, since loss of orthogonality is not as severe in DL as it is in UL.

Several users transmit over the same subcarrier. In essence this implies frequency-domain spreading, rather than time-domain spreading, as it is conceived in a DS-CDMA system. The channel equalization can be highly simplified in DL, because of the one-tap channel equalization benefit offered by OFDM.

In OFDM-CDMA, the flexibility lies in the allocation of all available codes to the users, depending on the required data rates. As OFDM-CDMA is applied using coherent modulation, the necessary channel estimation provides information about the subcarrier attenuations; this information can be used when performing an equalization in the receiver [28].

2.9.1.4 Relative Comparison

As shown in the previous discussions, we can consider OFDM-TDMA as the most basic multiple-access scheme, while OFDMA scheme is an extension of OFDM-

TDMA, and in turn, OFDM-CDMA scheme as an extension of OFDMA. Going from OFDM-TDMA to OFDM-CDMA, we have increased the level of flexibility in multiple-access of the system, but at the same time increased the complexity (see Fig. 2.10). The OFDM-CDMA shall observe all requirements from OFDMA, plus its own requirements. And similarly, OFDMA must fulfill all requirements of OFDM-TDMA.

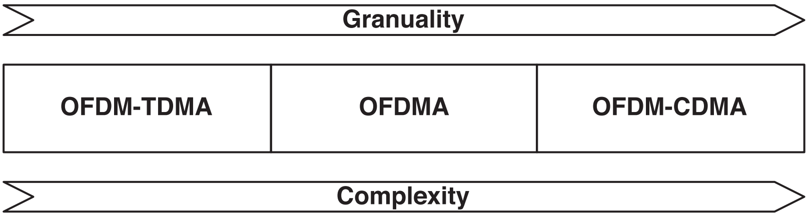

Fig. 2.10 Relative comparison of basic multi-carrier multiple-access techniques

Table 2.2 summarizes advantages and disadvantages of three basic multi-carrier multiple-access schemes.

Table 2.2 A summary of multiple access scheme

	Advantages	**Disadvantages**
OFDM-TDMA	Power savings (only receives own symbols) Simple resource allocation Easiest to implement	Relatively high latency Frequency-reuse factor ≥ 3 Lowest flexibility
OFDMA	Simple implementation Flexibility	Frequency-reuse factor ≥ 3
OFDM-CDMA	Spectral efficiency Frequency diversity MAI and inter-cell interference resistance Frequency-reuse factor = 1 Soft handover capability Highest flexibility	Requirement of power control Implementation complexity

OFDM-TDMA

OFDM-TDMA is simple to implement, but it may lack in highly delay-constraint system. For DL, basic OFDM-TDMA may not perform very well compared to other two schemes, but in UL, it may be very worthy. In UL, user time and frequency offset can cause real havoc in the system, and both OFDMA and OFDM-CDMA have to implement substantial procedure to combat the offsets, while OFDM-TDMA may be able to handle them quite easily. This is based on the fact that the entire bandwidth is allocated to a single user for several OFDM symbols, thus practically avoiding MAI.

OFDMA

The OFDMA scheme is distinguished by its simplicity, where the multi-access is obtained by allocating a fraction of subcarriers to different users. The benefit is that the receiver can be implemented in a relatively simple manner.

OFDMA is already in use in some standards, e.g., IEEE 802.16a, and can be used for both DL and UL. For the UL case, issues like synchronization are a major concern and are studied in several papers. Regarding the assignment of subcarriers, the literature provides no definitive answer whether it should be static/dynamic or contiguous/interleaved.

OFDM-CDMA

This scheme is potentially a very good scheme in DL due to its ability to exploit available frequency diversity, even coded-OFDMA can only make use of limited frequency diversity. It has been pointed that this scheme is vulnerable to near–far effect as a normal CDMA system is. Hence this scheme suits best mainly in an indoor DL scenario [29]. Now one is easily led to argue that in an indoor situation the coherence bandwidth is very large. In 5 GHz band, it ranges from 6 to 20 MHz. Thus to make use of its special advantage of providing frequency diversity, the system has to use a very wide band. Otherwise, even with a 20 MHz channel it will get as much frequency diversity as a coded interleaved OFDM system. In outdoor scenario, the loss of orthogonality due to severe channel coding may diminish the frequency diversity effect and introduce MAI to reduce the BER performance.

2.10 Single-Carrier vs Multi-carrier, TDE vs FDE

2.10.1 Single-Carrier FDE

A conventional anti-multipath approach, which was pioneered in voiceband telephone modems and has been applied in many other digital communications systems, is to transmit a single carrier, modulated by data using, for example, QAM, and to use an adaptive equalizer at the receiver to compensate for ISI [30]. Its main components are one or more transversal filters for which the number of adaptive tap coefficients is on the order of the number of data symbols spanned by the multipath. For tens of megasymbols per second and more than about 30–50 symbols ISI, the complexity and required digital processing speed become exorbitant, and this TDE approach becomes unattractive [31]. Therefore, for channels with severe delay spread, equalization in the frequency domain might be more convenient since the receiver complexity can be kept low. In fact, as for the OFDM, equalization is performed on a block of data at a time, and the operations on this block involve an efficient FFT operation and a simple channel inversion operation.

An SC system transmits a single carrier, modulated, for example, with QAM, at a high symbol rate. Linear FDE in an SC system is simply the frequency analog of what is done by a conventional time-domain equalizer. For channels with severe delay spread, SCFDE is computationally simpler than corresponding time-domain equalization for the same reason OFDM is simpler: because equalization is performed on a block of data at a time, and the operations on this block involve an efficient FFT operation and a simple channel inversion operation. Sari et al. [13, 32] pointed out that when combined with FFT processing and the use of a cyclic prefix, an SC system with FDE (SCFDE) has essentially the same performance and low complexity as an OFDM system. It is worth noting that a frequency domain receiver processing SC-modulated data shares a number of common signal processing functions with an OFDM receiver. In fact, as pointed out in Section 2.10.4, SC and OFDM modems can easily be configured to coexist, and significant advantages may be obtained through such coexistence.

Figure 2.11 shows conventional linear equalization, using a transversal filter with N tap coefficients, but with filtering done in the frequency domain. The block length N is usually chosen in the range of 64–2048 for both OFDM and SC-FDE systems.

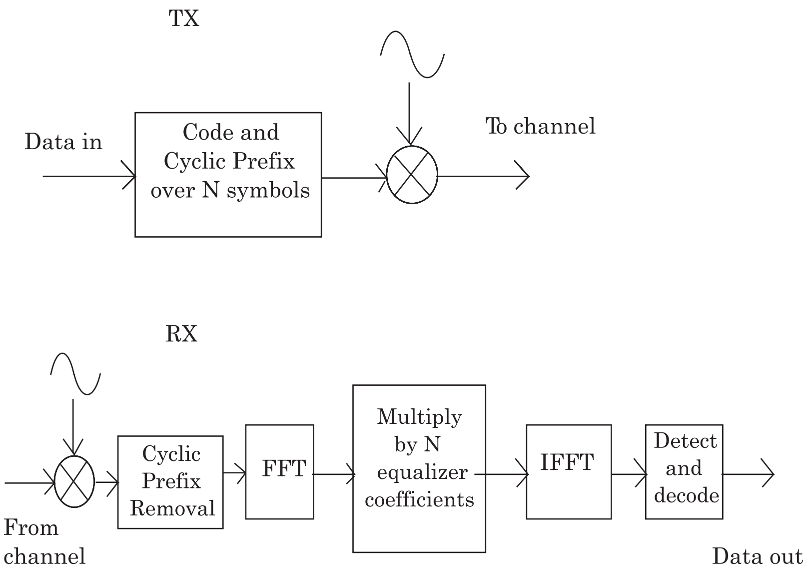

Fig. 2.11 SCFDE with linear FDE

A CP is appended to each block of N symbols, exactly as in OFDM. As an additional function, the CP can be combined with a training sequence for equalizer adaptation. An IFFT returns the equalized signal to the time domain prior to the detection of data symbols. Adaptation of the FDE's transfer function can be done with LMS, RLS, or LS minimization techniques, analogously to adaptation of time-domain equalizers [7, 33].

2.10.2 Single-Carrier vs Multi-carrier, FDE vs TDE

Some recent studies have clearly shown that the basic issue is not OFDM vs SC but rather frequency-domain equalization (FDE) vs time-domain equalization (TDE). FDE has several advantages over TDE in outdoor high-mobility propagation environments (usually with long tail channel impulse response).

The conventional approach to digital communications over dispersive channels is single-carrier transmission with time-domain equalization (TDE). TDE covers the simple linear equalizers, decision-feedback equalizers, as well as maximum-likelihood sequence estimation. These techniques have been in use for decades in digital microwave radio, and more recently in mobile radio systems. Although FDE was originally introduced in the late 1970s, it was not pursued and quickly disappeared from the literature [34].

Let us consider an FDE with N_{taps} taps. The FFT operator which forms the first stage of the equalizer gives N_{taps} signal samples denoted as $\left(Y_1, \ldots, Y_{N_{taps}}\right)$. These samples are sent to a complex multiplier bank whose coefficients are denoted as $\left(F_1, \ldots, F_{N_{taps}}\right)$. The coefficient values which minimize signal distortion are

$$F_n = \frac{H_n^*}{\mid H_n \mid^2} = \frac{1}{H_n}. \tag{2.31}$$

Clearly, each coefficient is only a function of the channel frequency response at the corresponding frequency, and the equalizer is easily adapted to channel variations even if the number of taps is very large [34].

From the above discussions, SC-TDE is sufficient for channels with a small delay spread, because these channels can be equalized using a small number of taps. In contrast, SCFDE or OFDM are required on channels with a large delay spread, as these channels require a large number of taps and this leads to convergence and tracking problems with SC-TDE. Indeed, the normalized complexity of both OFDM and SCFDE is proportional to $\log(N_{taps})$, whereas the complexity of SC-TDE grows linearly with N_{taps}. For N_{taps} large, the complexity considerations clearly favor the use of frequency-domain techniques. In fact, these considerations indicate that the real problem is not OFDM vs SC, but instead FDE vs TDE [34].

2.10.3 Analogies and Differences Between OFDM and SCFDE

There is a strong analogy between OFDM and SCFDE. Analyzing the operation principle of OFDM, Sari et al. [13] noticed a striking resemblance to frequency-domain channel equalization for traditional single-carrier systems, a concept proposed more than three decades ago [35]. The motivation for frequency-domain equalization was due to the ability of this technique to accelerate the initial convergence of the equalizer coefficients. With a frequency-domain equalizer at the receiver, single-carrier systems can handle the same type of channel impulse responses as OFDM systems. In both cases, time/frequency and frequency/time transformations are made. The difference is that in OFDM systems, both channel equalization and receiver decisions are performed in the frequency domain, whereas in SCFDE systems the receiver decisions are made in the time domain, although channel equalization is performed in the frequency domain.

From a purely channel equalization capability standpoint, both systems are equivalent, assuming they use the same FFT block length. They have, however, an essential difference: *since the receiver decisions in uncoded OFDM are independently made on different carriers, those corresponding to carriers located in a region with a deep amplitude depression will be unreliable*. This problem does not exist for SCFDE, in fact *once the channel is equalized in the frequency domain, the signal is transformed back to the time domain, and the receiver decisions are based on the signal energy transmitted over the entire channel bandwidth*. In other words, the SNR value that dictates performance (assuming that residual ISI is negligible) corresponds to the average SNR of the channel. In fact, as noted in [13], the effect of the deep nulls in the channel frequency response is spread out over all symbols by the IFFT operation. Consequently, the performance degradation due to a deep notch in the signal spectrum remains small with respect to that suffered by OFDM.

The foregoing analysis indicates that with FDE, SC transmission is substantially superior to OFDM signaling. Without channel coding, OFDM is in fact not usable on fading channels, as deep notches in the transmitted signal spectrum lead to an irreducible BER. In order to work satisfactorily, *OFDM requires ECC with frequency-domain interleaving so as to scatter the signal samples falling in a spectral notch*. In this case, the interleaver uniformly distributes the low-SNR samples over the channel bandwidth. *In contrast, SCFDE can work without ECC.*

The main hardware difference between OFDM and SCFDE is that for SCFDE the transmitter's IFFT block is moved to the receiver. The complexities are the same. *Both OFDM and SCFDE can be enhanced by* adaptive modulation and *space diversity* [36].

The use of SC modulation and FDE by processing the FFT of the received signal has several attractive features:

- SC modulation has reduced PAPR requirements with respect to OFDM, thereby allowing the use of less costly power amplifiers;
- its performance with FDE is similar to that of OFDM, even for very long channel delay spread;
- frequency-domain receiver processing has a similar complexity reduction advantage with respect to that of OFDM: complexity is proportional to log of multipath spread;
- coding, while desirable, is not necessary for combating frequency selectivity, while it is needed in nonadaptive OFDM;
- SC modulation is a well-proven technology in many existing wireless and wireline applications, and its RF system linearity requirements are well known.

Comparable SCFDE and OFDM systems would have the same block length and CP lengths. The CP at the beginning of each block (Fig. 2.12), used in both SCFDE and OFDM systems, has two main functions:

- it prevents contamination of a block by ISI from the previous block;
- it makes the received block appear to be periodic of period N, which is essential to the proper functioning of the FFT operation.

If the first and the last N_{CP} symbols are identical unique word sequences of training symbols, the overhead fraction is $\frac{2N_{CP}}{N+2N_{CP}}$.

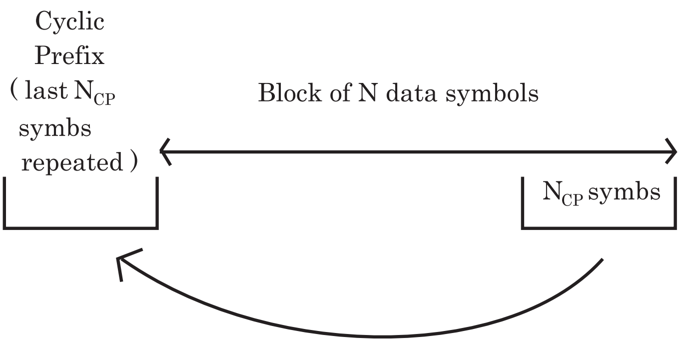

Fig. 2.12 Block processing in FDE

The following considerations provide a further support to the thesis of the similarity between SCFDE and OFDM. Precoding in OFDM disperses the energy of symbols over the channel bandwidth, i.e., it restores the frequency diversity broken by the IFFT operator. A common precoding matrix is the Walsh–Hadamard matrix which uniformly spreads the symbol energy across the channel bandwidth using orthogonal spreading sequences. Another precoding matrix that uniformly spreads the symbol energy over the channel bandwidth is the FFT matrix. This matrix cancels the IFFT matrix that generates the OFDM signal and the system reduces to SCFDE. From this discussion, it is clear that precoded OFDM mimics SCFDE. That is, *by precoding OFDM in order to restore frequency diversity, we get an SCFDE-type system* [34].

2.10.4 Interoperability of SCFDE and OFDM

Figure 2.13 shows block diagrams for OFDM and SC systems with linear FDE. It is evident that the two types of systems differ mainly in the placement of the IFFT operation: in OFDM it is placed at the transmitter to multiplex the data into parallel subcarriers; in SC it is placed at the receiver to convert FDE signals back into time-domain symbols. The signal processing complexities of these two systems

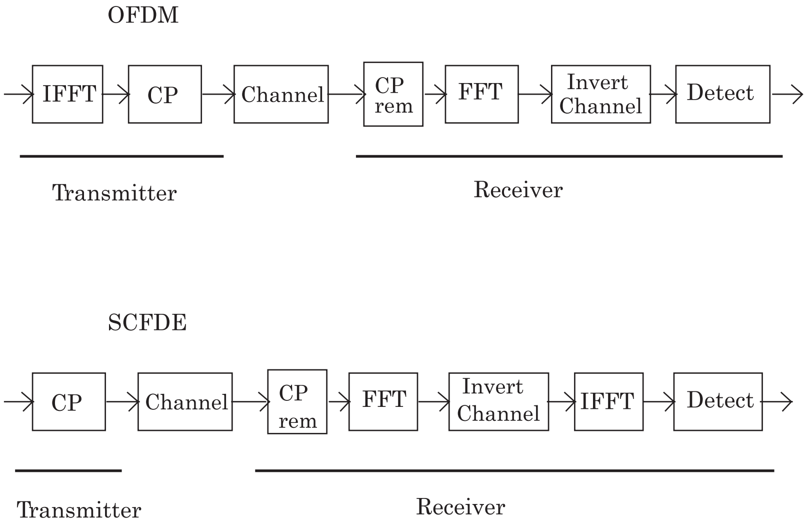

Fig. 2.13 OFDM and SCFDE signal processing similarities and differences

are essentially the same for equal FFT block lengths [31]. A dual-mode system, in which a software radio modem can be reconfigured to handle either SC or OFDM signals, could be implemented by switching the IFFT block between the transmitter and receiver at each end of the link, as suggested in Fig. 2.14. *There may actually be an advantage in operating a dual-mode system, wherein the base station uses an OFDM transmitter and an SC receiver, and the subscriber modem uses an SC transmitter and an OFDM receiver*, as illustrated in Fig. 2.15. This arrangement – OFDM in the downlink and SC in the uplink – has two potential advantages [31]:

- concentrating most of the signal processing complexity at the hub or base station. The hub has two IFFTs and one FFT, while the subscriber has just one FFT;

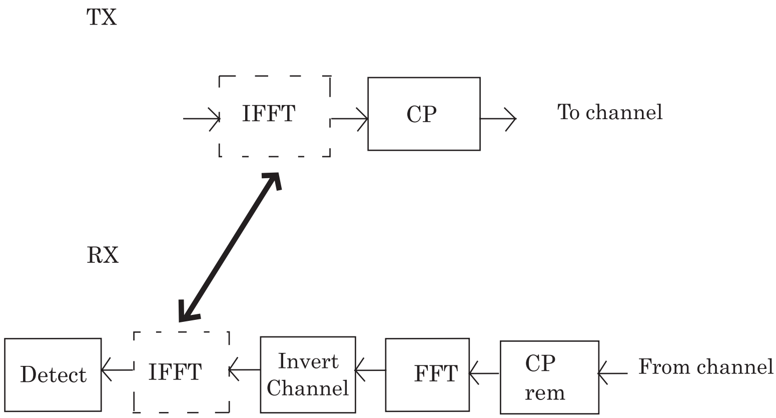

Fig. 2.14 Potential interoperability of SCFDE and OFDM: a “convertible” modem

- the subscriber transmitter is SC, and thus inherently more efficient in terms of power consumption due to the reduced power backoff requirements of the SC mode. This may reduce the cost of a subscriber's power amplifier.

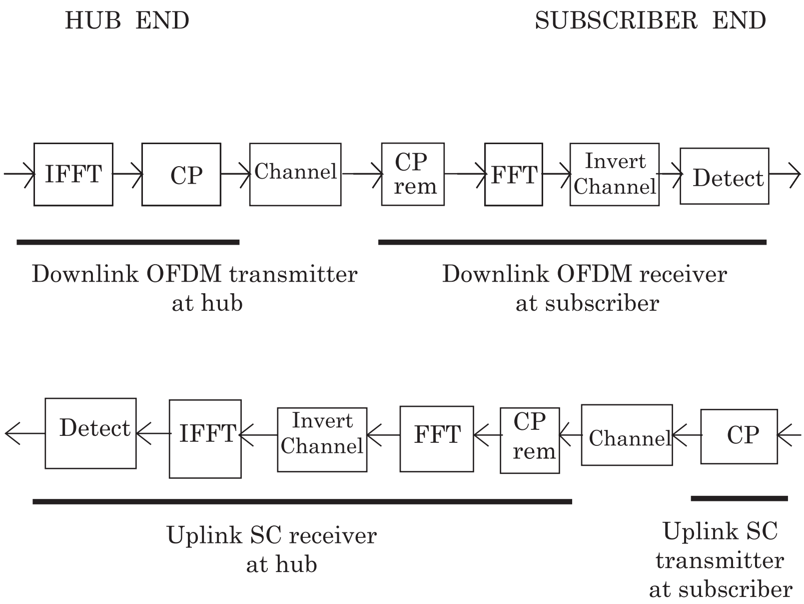

Fig. 2.15 Coexistence of SCFDE and OFDM: uplink/downlink asymmetry

2.11 OFDMA: An Example of Future Applications

OFDMA will be used as an access scheme in many high data rate and high-quality future services and applications. As an example, the ITU is currently working on specifying the system requirements toward next-generation mobile communication systems, called IMT-A. The IMT-A systems are expected to fulfill the requirements of so-called 4G systems and believed to be operational around year 2015. One of the key features for IMT-A is enhanced peak data rates to support advanced services and applications in the order of 100 Mbit/s for high-mobility and 1 Gbit/s for low-mobility conditions [37]. In order to support such high data rates the WRC 07 has identified the allocation of the following additional spectrum bands, 450–470 MHz, 698–862 MHz, 790–862 MHz, 2.3–2.4 GHz, and 3.4–3.6 GHz. Some of these bands support the channel bandwidth up to 100 MHz. It is envisioned that such high channel bandwidth in the new frequency bands will be optimized for small cell and low mobility scenarios such as dense urban and hot spot areas, especially indoor.

In order to provide high data rate and high-quality coverage in indoor local area, the solutions are emerging in the form of new devices and networks. These devices are expected to be deployed at very large scale in random manner to support the individual coverage in small area, accessing the spectrum from a common pool. In that situation the interference becomes the main concern. An efficient technique will be essential to support FSU to allow coexistence of such devices in the given area. FSU basically means allocation of spectrum by several devices over the same spectrum pool in flexible manner using the same radio access technology. OFDMA is considered as the most promising technique to facilitate FSU, because of its natural attribute of allocating the spectrum in flexible manner.

The following example available in [38] demonstrates this capability of OFDMA to allocate the spectrum in flexible manner. The example considers the deployment of four devices in an indoor small area. The chosen carrier frequency is 3.5 GHz with 100 MHz spectrum bandwidth, which is one of the newly allocated spectrum bands by WRC 07. TDD with perfect synchronization and equal uplink and downlink ratio is assumed. A transmission frame of 10 ms duration is considered. The indoor path loss propagation model and multipath channel model are based on the description presented in [39] which is proposed to ITU-R for evaluations of IMT-A systems. SISO antenna configuration is taken. The FSU target SINR threshold is defined and has to be overcome in order to allocate a spectrum unit, and allows coexistence of several devices in the small area, ranging from −10 to 20 dB in steps of 5 dB [38]. The transmission characteristics of OFDMA for this scenario are listed in Table 2.3. Figure 2.16 demonstrates the flexibility of OFDMA in spectrum allocation at different FSU target SINR thresholds, presented together with the fixed spectrum allocation of 1, 1/2, and 1/4 frequency reuse schemes. The performance is measured in terms of average carried cell load against the average offered cell load. The impact of different FSU target SINR thresholds can be clearly seen in the figure. At very low SINR threshold (i.e. −10 and −5 dB) the average carried cell load is very close to the offered load, which is very similar to reuse 1 case [38]. By lowering the threshold, higher amount of overlapping is allowed, resulting into higher average carried cell load. Instead, at very high SINR threshold the average carried cell load is lower compared to the offered load and becomes very close to 1/4 frequency reuse scheme [38], which is due to nearly orthogonal spectrum allocation. The carried cell load of 1/2 frequency reuse scheme lies between that of 1 and 1/4 frequency reuse schemes. Therefore, it is reflected that the OFDMA has the attribute to span over all the possibilities of fixed spectrum allocation schemes depending on the required SINR threshold. This allows coexistence of several devices in the small geographical

Table 2.3 Example of OFDMA characteristics used in local area indoor deployment toward next-generation mobile communication systems

Parameters	Settings
Carrier frequency	3.5 GHz
FFT size	2048
Number of subcarriers	1500
Sub carrier spacing	60 kHz
Transmission frame duration	10 ms
Slot duration	1 ms
Number of slots in one frame	10

area by dynamically and flexibly adapting the spectrum allocation. This feature of OFDMA provides self-adjusting and self-optimizing capabilities to the devices, and therefore it can be considered as a promising technology for the future applications.

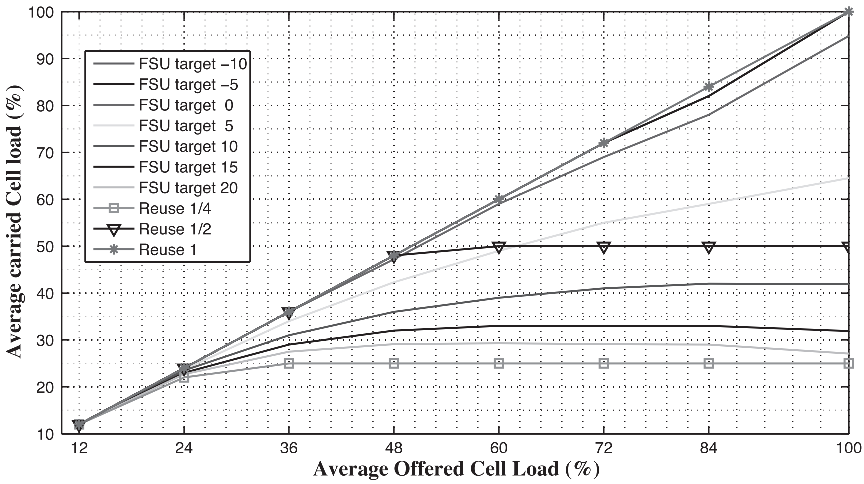

Fig. 2.16 Average carried cell load with different FSU target SINR thresholds using OFDMA [38] (©[2008] IEEE, Reprinted with permission, DySPAN 2008)

2.12 Conclusions

In this chapter, we have discussed the basics of multi-carrier transmission corresponding to current and future 4G wireless systems. It is evident that multi-carrier transmission is a very useful technique in combating the adverse effects of wireless channels and making use of the adversity to the benefit of the system. Modified single-carrier transmissions such as SC-FDE- and SC-FDMA-type transmission techniques also provide similar benefits. Thus, the transmission techniques mentioned in this chapter will be part and parcel of all (or most) immediate future wireless systems.

Section 2.1 emphasizes that outlights that future wireless applications will demand high data rate communication; this is not going to be an easy task, when dealing with the unpredictable wireless channel. The idea of multi-carrier transmission has emerged recently to be used for combating the hostile wireless channel and providing high data rate communications. OFDM is a special form of multi-carrier transmission where all the subcarriers are orthogonal, and it promises a high user data rate transmission capability at a reasonable complexity and precision.

Although OFDM has only recently been gaining interest from telecommunications industry, it has a long history of existence, and this is discussed in Section 2.2, where considerations about history and development of OFDM have been made. While Section 2.3 discusses spots the rationale behind using multi-carrier transmission, a general OFDM transceiver is described in Section 2.4. The analytical model for OFDM transceiver is presented in Section 2.5.

Advantages and disadvantages of this technique are discussed in Sections 2.6 and 2.7, respectively. Section 2.8 relates OFDM with a cellular system, considering system design requirements and parameters; multiple access techniques based on OFDM modulation are described in Section 2.9. Analogies, differences, and potential interoperability of OFDM and SCFDE are discussed in Section 2.10. Finally, Section 2.11 highlights an example of possible future application of OFDMA for spectrum sharing and FSU.

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http://www.springer.com/978-1-4419-0672-4

New Directions in Wireless Communications Research
Tarokh, V. (Ed.)
2009, XXVI, 469 p., Hardcover
ISBN: 978-1-4419-0672-4