2 Introduction to OFDM

Orthogonal Frequency Division Multiplexing (OFDM) is a multi-carrier modulation scheme that transmits data over a number of orthogonal sub-carriers. A conventional transmission uses only a single carrier modulated with all the data to be sent. OFDM breaks the data to be sent into small chunks, allocating each sub-data stream to a sub-carrier and the data is sent in parallel orthogonal sub-carriers. As illustrated in Figure 1, this can be compared with a transport company utilizing several smaller trucks (multi-carrier) instead of one large truck (single carrier).
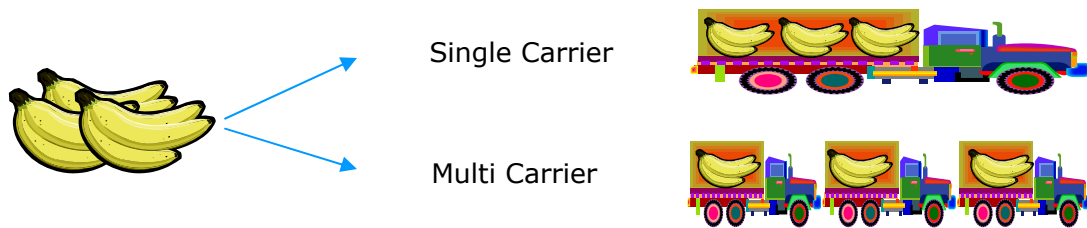
Single Carrier

Multi Carrier

Figure 1   Single carrier vs. multi-carrier transmission

OFDM is actually a special case of *Frequency Division Multiplexing* (FDM). In general, for FDM, there is no special relationship between the carrier frequencies, f_1, f_2 and f_3. Guard bands have to be inserted to avoid *Adjacent Channel Interference* (ACI). For OFDM on the other hand, there must be a strict relation between the frequency of the sub-carriers, i.e. $f_n = f_1 + n \cdot \Delta f$ where $\Delta f = 1/T_U$ and T_U is the symbol time. Carriers are orthogonal to each other and can be packed tight as shown in Figure 2.
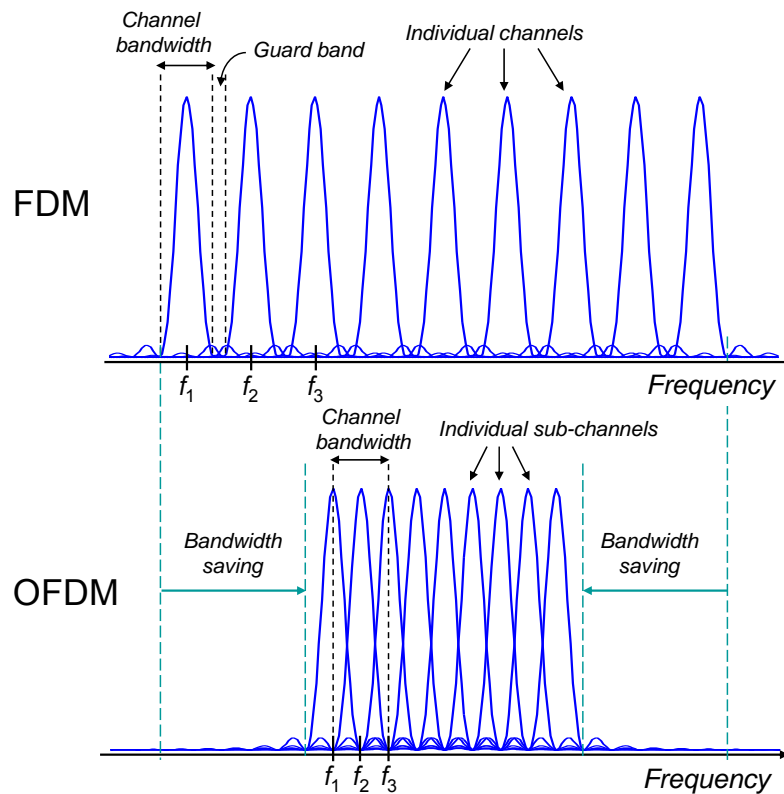
Figure 2   FDM vs. OFDM

Splitting the channel into narrowband channels enables significant simplification of equalizer design in multipath environments. Flexible bandwidths are enabled through scalable number of sub-carriers.

Effective implementation is further possible by applying the *Fast Fourier Transform* (FFT). Dividing the channel into parallel narrowband sub-channels makes coding over the frequency band possible (COFDM). Moreover, it is possible to exploit both time and frequency domain variations, i.e. time and frequency domain adaptation.

2.1 OFDM basic concept

A baseband OFDM transmission model is shown in Figure 3. It basically consists of a transmitter (modulator, multiplexer and transmitter), the wireless channel, and a receiver (demodulator).
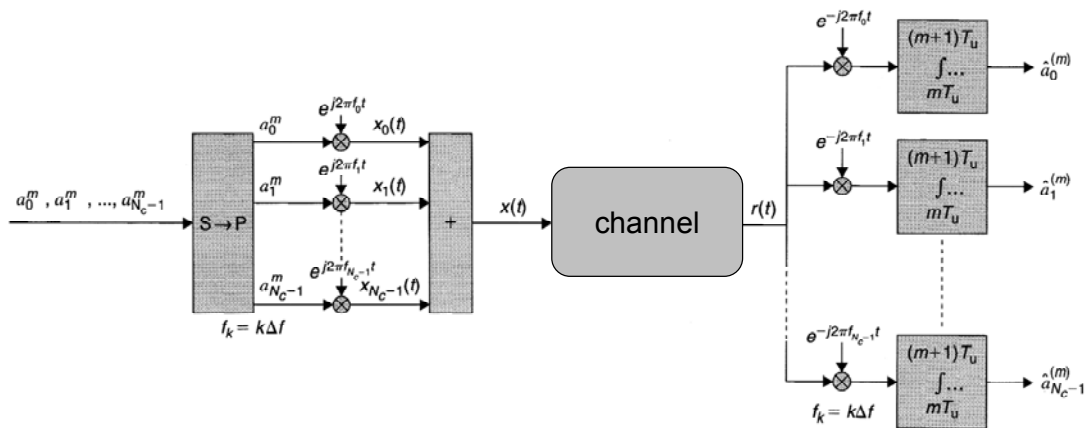
Figure 3   Basic baseband OFDM transmission model

In Figure 3, a bank of modulators and correlators is used to describe the basic principles of OFDM modulation and demodulation. This is not practically feasible, and the specific choice of sub-carrier spacing being equal to the per carrier symbol rate $1/T_U$ makes a simple and low complexity implementation using *Fast Fourier Transform* (FFT) processing possible as shown in Figure 4. For more details on the FFT implementation we refer to [Nee00].
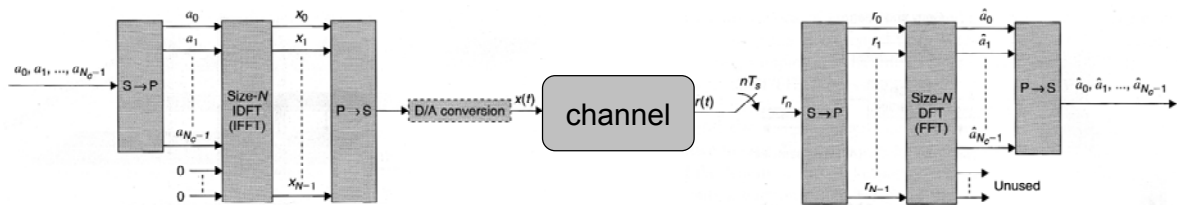

Figure 4   Transmitter and receiver by using FFT processing

In the consecutive subsections we will discuss the most important properties of the OFDM transmitter (Section 2.1.1), OFDM signal properties (Section 2.1.2), the OFDM channel (Section 2.1.3), and the OFDM receiver (Section 2.1.4)

2.1.1 Orthogonality principle

The essential property of the OFDM signal is the orthogonality between the sub-carriers. Orthogonal means "perpendicular", or at "right angle".

Two functions, $x_q(t)$ and $x_k(t)$, are orthogonal over an interval [a, b] if the inner product between them is zero for all q and k, except for the case that $q = k$, i.e. when $x_q(t)$ and $x_k(t)$ are the same function. Mathematically this can be written as:

$$\left\langle x_q, x_k \right\rangle = \int_a^{b_U} x_q(t) \cdot x_k(t) dt = \begin{cases} 1, & k = q \\ 0, & k \neq q \end{cases} \tag{1}$$

If we look at receiver branch k in Figure 3, the output of the integrator can be expressed as follows:

$$\frac{1}{T_U}\int_0^{T_U} r(t)\cdot e^{-j2\pi k\Delta ft}\,dt = \frac{1}{T_U}\int_0^{T_U}\left(\sum_{q=0}^{N_C-1} a_q\cdot e^{j2\pi q\Delta ft}\right)\cdot e^{-j2\pi k\Delta ft}\,dt$$

$$= \sum_{q=0}^{N_C-1}\frac{a_q}{T_U}\int_0^{T_U} e^{j2\pi(q-k)\frac{1}{T_U}t}\,dt = \begin{cases} a_k\,, & k=q \\ 0\,, & k\neq q \end{cases}$$

(2)

In this example we assume no noise or multipath degradation of the signal (ideal channel). We see that the last integral satisfies the orthogonality definition. Consequently, the harmonic exponential functions (sine wave carriers) with frequency separation $\Delta f = 1/T_U$ are orthogonal.

This property gives optimum spectrum utilization and makes it possible to separate the sub-carriers in the receiver. Figure 5 is an attempt to illustrate how the orthogonality works in the time domain, if e.g. x_q is the received sub-carrier, and x_k represents the local oscillator as shown in Figure 3. When integrating received power over one symbol period, T_U, the output of the correlators is zero for any combination, except when $k = q$.

When the sub-carriers are modulated with a rectangular pulse the sub-carrier spectrum becomes as shown in Figure 6. This implies that in the frequency domain, the power of sub-carriers approaches zero at the centre frequency of the neighbouring sub-carriers as shown in Figure 7. The figure shows the power spectrum of the individual sub-carriers of an OFDM spectrum.
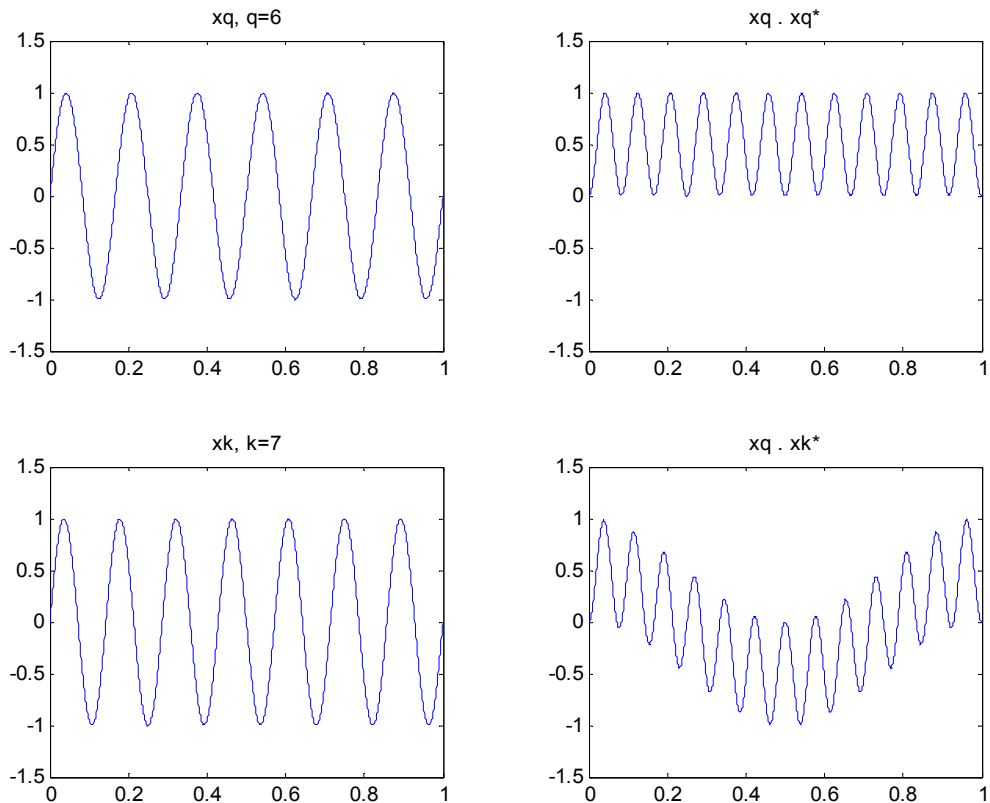
Figure 5   Orthogonality principle in the time domain. Leftmost graphs show the input signal shapes over one symbol period. The rightmost graphs show the integrand in the case of equal signal (upper) and orthogonal signal (lower). It is easily seen that the total area under the curve when q = k is positive, while it sums up to zero over one symbol period when the frequencies are different and spaced $1/T_U$ apart
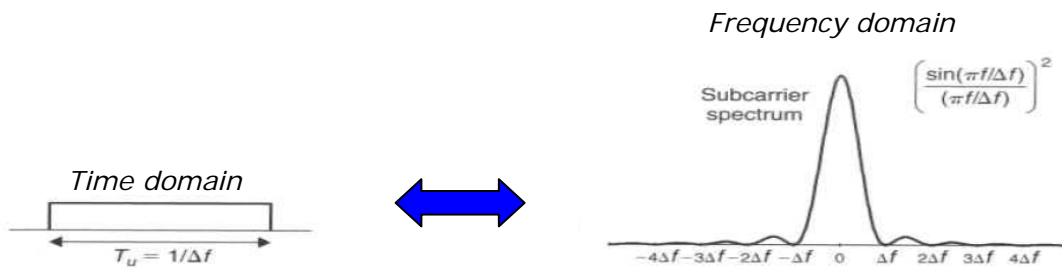

Figure 6   Time and frequency domain representation of the baseband signal
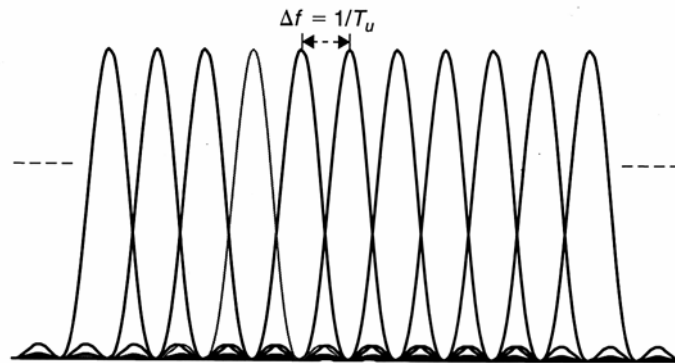
Figure 7   Power spectrum of orthogonal sub-carriers

A real OFDM power spectrum will not look like the one in Figure 7, because a power based measurement cannot distinguish the separate sub-carriers. Figure 8 shows a field measurement of a mobile WiMAX spectrum with a bandwidth of 5 MHz. The signal consists of 360 active sub-carriers. The FFT-size is 512. The amplitude variations are due to frequency selective fading caused by multipath transmissions. This is treated in section 2.1.3.
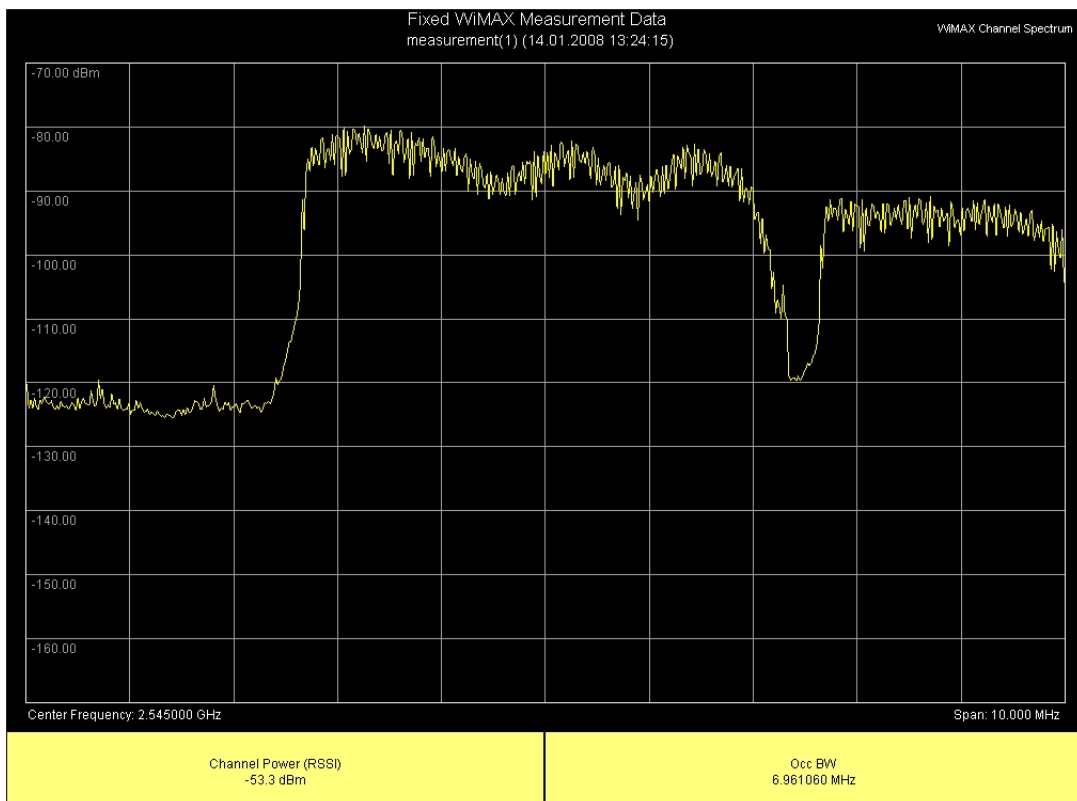

Figure 8   Field measurement of an OFDM spectrum (WiMAX) in a LOS environment

2.1.2 Instantaneous power variations

An OFDM signal consists of a number of independently modulated symbols.

$$x(t) = \sum_{k=0}^{N_c-1} a_k \cdot e^{(j2\pi k\Delta f\, t)} \tag{3}$$

Adding carriers with different frequencies and modulation gives large amplitude variations. This is the Peak Power Problem of OFDM. It can be shown that the maximum value of the *Peak to Average Power Ratio* (PAPR) is the same as the number of sub-carriers:

$$PAPR_{\max} = N_C \tag{4}$$

Figure 9 shows a simulated waveform of an OFDM-signal with 8 sub-carriers and BPSK modulation. The expanded part of the graph shows that the amplitude variations are large and that the maximum value of the sum can be as high as 8.
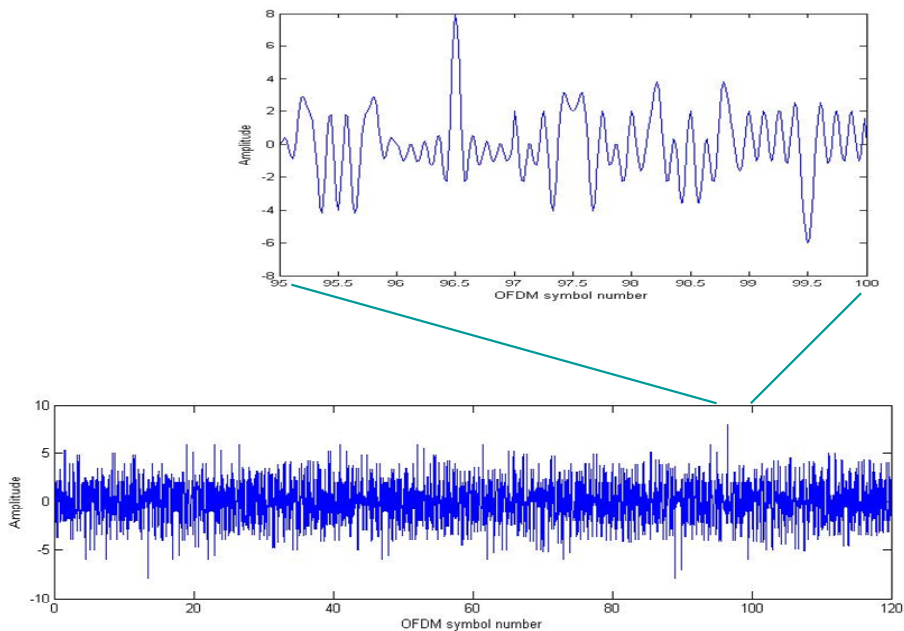

Figure 9   Amplitude variations in an OFDM signal. Example is 8 sub-carriers and BPSK modulation

A large PAPR is negative for the power amplifier efficiency since a backoff is needed to avoid amplitude distortion and the following harmonic frequencies.

Figure 10 shows a typical input-output characteristic of a power amplifier. In order to avoid or limit signal distortion input signals must be kept below the non-linear area. The consequence is that the amplifier is not fully utilized.
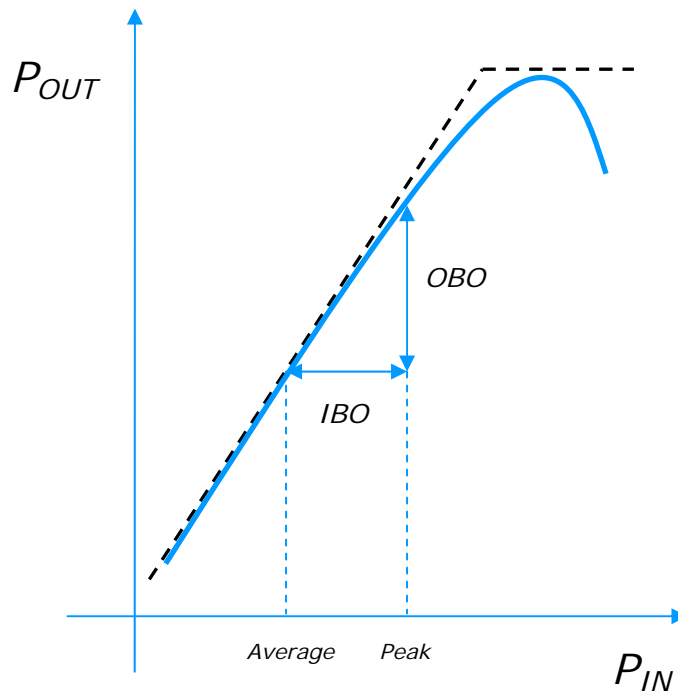
AM/AM characteristic

Figure 10   Typical input-output characteristics of a power amplifier showing the relation between output backoff (OBO) and input backoff (IBO)

Different measures to avoid large PAPRs are used and are classified in three major techniques:

- Signal distortion techniques
    - o Clipping (signal distortion, out of band radiation, window)
    - o Peak windowing (reduce the out of band radiation)
    - o Peak cancellation (linear, can avoid out of band radiation)
- Coding techniques
    - o Special FEC codes that excludes OFDM symbols with a large PAPR (decreasing the desired PAPR this way may decrease achievable coding gain).
    - o Tone reservation is another coding technique where a subset of OFDM sub-carriers are not used for data transmission but instead are modulated to suppress the largest peaks of the overall OFDM signal.
    - o Pre-filtering or pre-coding, linear processing applied to the OFDM-symbols before OFDM modulation.
- Scrambling techniques
    - o Different scrambling sequences are applied, and the one resulting in the smallest PAPR is chosen

PAPR reduction techniques applied to different wireless standards must partly be described in the standards, as e.g. coding and scrambling. Signal distortion techniques however can be a pure implementation aspect, but the use of such usually means a reduced BER performance in the receiver.

No special technique seems to be specified in WiMAX, but in E-UTRA the uplink transmission is based on a linear pre-coding technique called DFT-spread OFDM, which effectively reduces the PAPR with 2-3 dB [Dahl07] [Myu06b]. This is detailed a bit more in section 3.3.

2.1.3 Wireless channel influence

A wireless channel introduces impairments to the signal, mainly due to multipath transmission as shown in Figure 11.
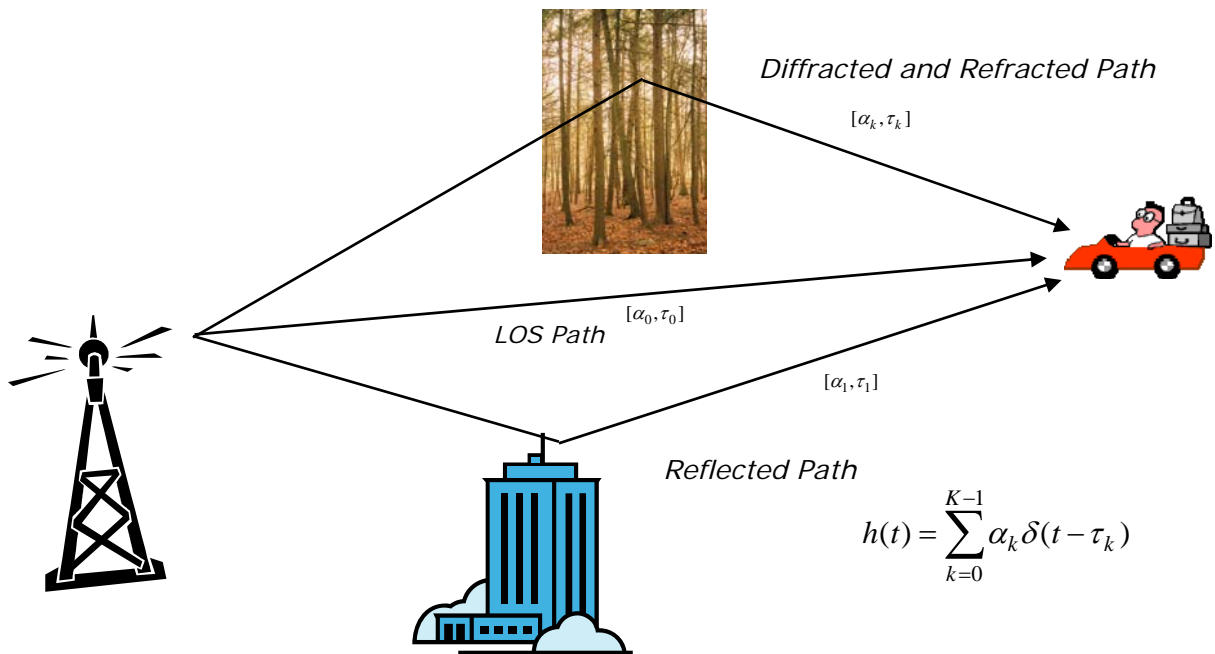

Diffracted and Refracted Path

$[\alpha_k, \tau_k]$

LOS Path $[\alpha_0, \tau_0]$

$[\alpha_1, \tau_1]$

Reflected Path

$$h(t) = \sum_{k=0}^{K-1} \alpha_k \delta(t - \tau_k)$$

Figure 11   The multipath channel

Figure 12 (left) shows a measured channel impulse response, both the direct path signal and the reflected (echoed) signals. In addition, Figure 12 (right) illustrates a simplification of the impulse response.
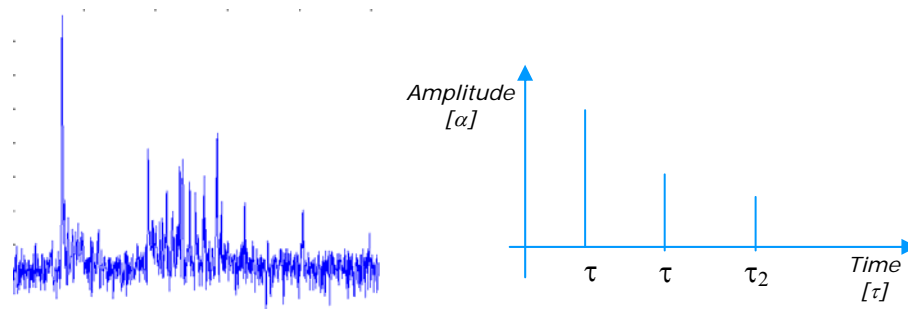

Amplitude [α]

τ τ τ_2 *Time [τ]*

Figure 12   Multipath channel impulse response. Left: measured. Right: simplified two ray model

The consequence of multipath propagation is that time dispersion is introduced in the signal. Figure 13 illustrates the effect in the time domain and how a *cyclic prefix* (CP) may be used to mitigate the effect. Time-adjacent symbols start to overlap and *inter-symbol-interference* (ISI) is introduced (Figure 13a). In Figure 13b the symbol is prolonged by adding a guard time between the symbols, but just adding an "empty" guard time destroys the orthogonality and introduces *inter-carrier interference* (ICI). In order to avoid this and thus to maintain the orthogonality, the prefix is made cyclic by taking a copy of the last part of the symbol and put it in front (Figure 13c). The prefix time must be longer than the longest excess delay which can occur in the channel.

a) Multipath introduces *inter-symbol-interference* (ISI)
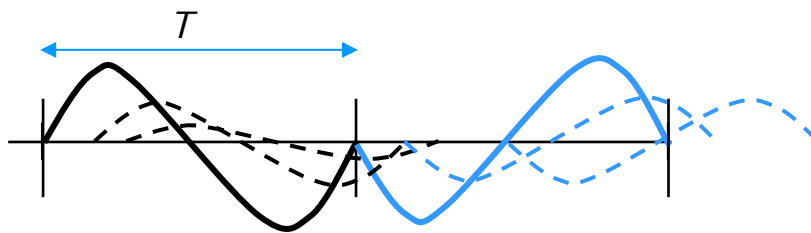
b) Prefix is added to avoid ISI
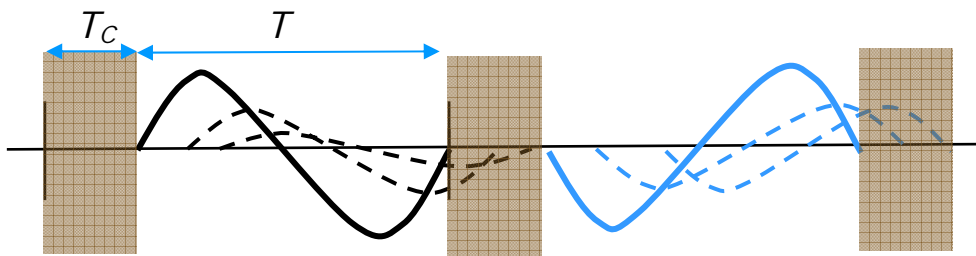
c) The prefix is made cyclic to avoid *inter-carrier-interference* (ICI)
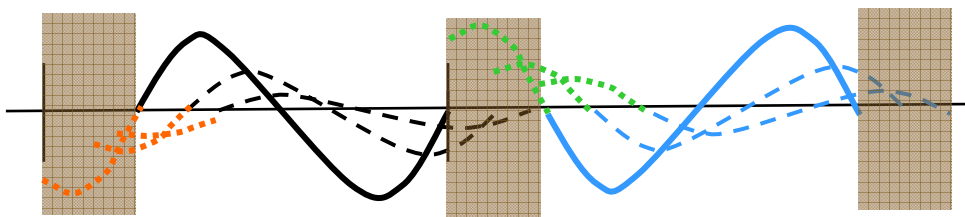(maintain orthogonality)

Figure 13   Time dispersion due to multipath propagation and the method of cyclic prefix insertion

Due to the large bandwidth of an OFDM signal, the multipath effect is frequency dependent and results in frequency selective fading as shown in Figure 14.
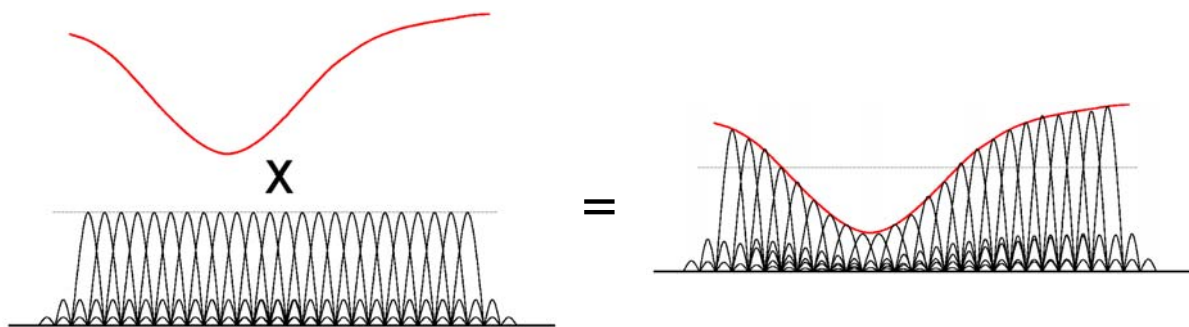
Figure 14   Frequency selective fading of an OFDM signal

Figure 15 shows a measured OFDM spectrum (mobile WiMAX, 5 MHz) in an NLOS scenario. A strong multipath component is causing severe frequency selective fading.
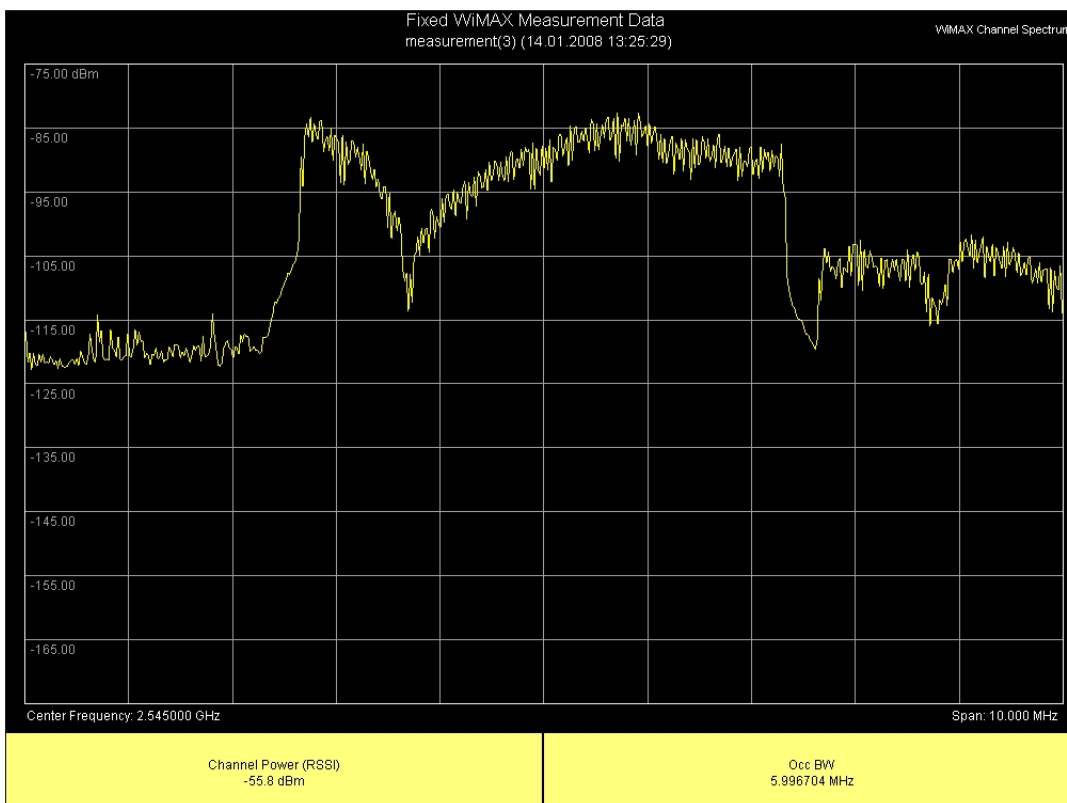

Figure 15   Measured OFDM-spectrum in an NLOS scenario showing how multipath reflections cause severe frequency selective fading

Coding should be performed over several uncorrelated carriers to utilize the frequency diversity (frequency interleaving). It is equivalent to coding in time domain to achieve time diversity (time interleaving). Often we will see the term *Coded OFDM* (COFDM) used in this respect. Especially the digital terrestrial broadcast standards DVB-T and DVB-H use the term COFDM.

In reality, any OFDM and OFDMA based standard uses frequency domain coding to exploit the frequency diversity.

2.1.4 Signal detection and demodulation

Time and frequency properties of the OFDM signal are tightly coupled, and both must be properly recovered in the receiver.

When performing timing recovery, the sum of the timing error ($\Delta\tau$ and the maximum excess delay (τ_{max}), should be within the prefix time. Then, the only effect is a phase rotation that increases with increasing distance from the carrier (centre frequency). However, a carrier frequency synchronization error will introduce phase rotation, amplitude reduction and ICI. Frequency offsets of up to 2% of Δf are negligible and even offsets of 5-10% can be tolerated in many situations.

To help the receiver in performing these tasks, pilot or reference symbols are inserted in the OFDM signal. These are known signal sequences spread out in time and frequency which the receiver can use to recover both time and frequency references. Additionally, some of these are usually tailored to enable reliable channel estimations. The simplest way is to reserve a number of sub-carriers to carry reference signals as shown in Figure 16. In this case, the sub-carriers are often called pilot signals. More common is to reserve time/frequency symbols as shown in Figure 17. In this case, they are not transmitted continuously, neither in time nor frequency.
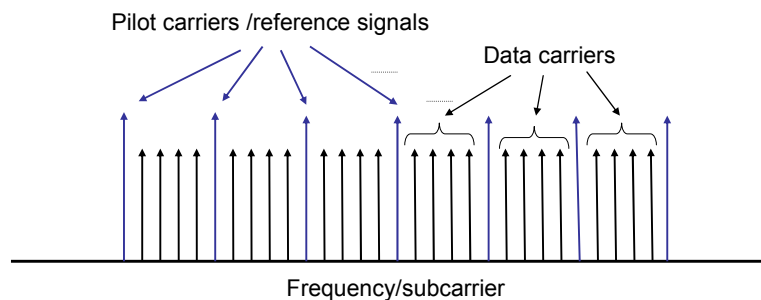

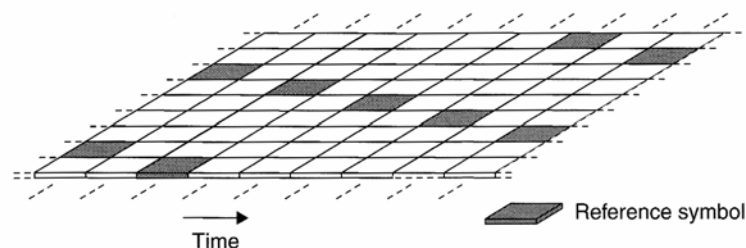*Figure 16   Pilot carriers in an OFDM signal*

Figure 17   Time-frequency grid with reference symbols

2.2 Choosing the OFDM parameters

We have now defined and described the important properties of the OFDM-signal, and we shall now discuss the criteria for designing a system based on OFDM.

Some of the key parameters for the OFDM signal are:

- Sub carrier spacing (Δf) and Symbol time (T_U)

- Number of sub-carriers(N_C)

- The cyclic prefix length (T_{CP})

- Pulse shape, or windowing function.

2.2.1 Sub-carrier spacing and symbol time

As we have seen, symbol time and sub-carrier spacing are inverse entities. Two factors determine the selection of the OFDM sub-carrier spacing, Δf:

- It is preferable to have as small SC spacing as possible, since this gives a long symbol period and consequently the relative cyclic prefix overhead will be minimized.

- Too small SC spacing increases the sensitivity to Doppler spread and different kinds of frequency inaccuracies.

Doppler spread is typical for mobile systems and the amount is directly limited by the relative velocity between the mobile and the base station. Frequency variations due to Doppler spread leads to losing the orthogonality in the receiver and ICI occurs. Dependent on the targeted mobility for the system and the allowed amount of ICI, the sub-carrier distance can be selected. According to [Dahl07] a normalized Doppler spread ($f_{Doppler}/\Delta f$) of 10 % leads to a *Signal to Interference Ratio* (SIR) of 18 dB.

If we want to design a system in the 2 GHz band (λ = 15 cm) supporting terminal mobility up to v = 200 km/h (= 55.5 m/s), we get a maximum Doppler frequency of $f_{Doppler} = v/\lambda$ = 370 Hz. If we require an SIR of 30 dB, we can allow approximately 2.5 % normalized Doppler spread. This gives us a sub-carrier spacing of 14.8 kHz, which is quite close to the choice made in E-UTRA.

This is a very simple example, and in a real design situation there are other factors which must be taken into account as well. Some of the effects of varying the sub-carrier spacing are shown in Figure 18.
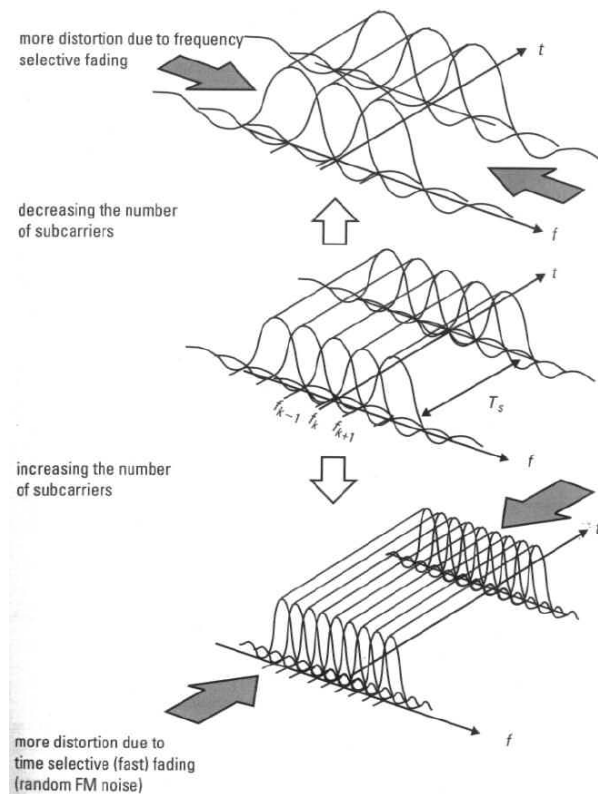
Figure 18   Effects of changing the sub-carrier spacing

2.2.2 Number of sub-carriers

When the sub-carrier spacing is determined, the available bandwidth determines the number of sub-carriers, N_C, to be used. The basic bandwidth of an OFDM signal is $N_C \cdot \Delta f$. However, the frequency spectrum of a basic OFDM signal falls off very slowly outside the basic bandwidth, and lower and upper guard bands must be inserted. By applying pulse shaping or windowing, the out-of-band emissions can be reduced. In practice, typically 10 % guard band is needed [Dahl07], implying that of a spectrum allocation of 5 MHz, 4.5 MHz is usable. For the E-UTRA with 15 kHz sub-carrier spacing this means that approximately 300 sub-carriers can be exploited in a 5 MHz channel. For WiMAX with 10.94 kHz sub-carrier spacing, 400 sub-carriers can be used.

2.2.3 Cyclic prefix length

The *cyclic prefix* (CP) length, T_{cp}, should cover the maximum length of the time dispersion. Increasing T_{cp} without decreasing Δf implies increased overhead in power and bandwidth.

Too short CP gives ISI. On the other hand, increasing the relative length of the CP leads to increased power loss. Thus, choosing T_{cp} is a trade-off between power loss and time dispersion.

The maximum time dispersion experienced depends on the radio channel and its multipath properties as discussed earlier in section 2.1.3. If for example we target our system for ranges up to 10 km, an excess delay of reflected and diffracted signals corresponding to Δs = 2 km is easily encountered. The excess delay is then $\Delta t = \Delta s/c$ = 6.7 µs, which could be used as the value for the CP.

In a real channel, the *power delay profile* (PDP) often follows an exponential decay function, and our design criteria will be the amount of remaining energy in the tail of the PDP which is tolerated to interfere with the next symbol (see Figure 19).
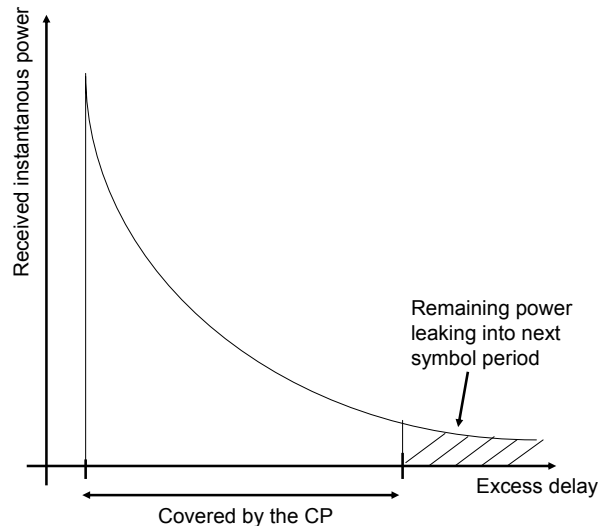

Figure 19   Channel power delay profile (PDP) and cyclic prefix (CP) dimensioning

The PDP is dependent on the environment, thus the system must be designed bearing this in mind. Multipath channel measurements on 900 MHz and 1.7 GHz done by Telenor R&I in 1990 and 1991 [Løv92] [Ræk95] showed that for urban areas (downtown Oslo) the *delay spread* (DS) in 90 % of the cases were below 0.7 μs, which should be well below the chosen CP lengths of E-UTRA and Mobile WiMAX (approximately 5 and 10 μs, resp). However for different rural environments, the DS values could be between 5 and 20 μs in 90 % of the cases. These kinds of environments may be more challenging.

2.2.4 Pulse shaping and windowing functions

As mentioned when discussing the number of sub-carriers to use, the spectrum of a basic OFDM signal falls off very slowly outside the basic bandwidth. Especially it falls off much slower than for WCDMA. The reason is the use of rectangular pulse shaping which leads to high side lobe level. An example is shown in Figure 20 for 16, 64 and 256 sub-carriers. For a larger number of sub-carriers the spectrum falls off more rapidly because side lobes are closer together.

Pulse-shaping or time-domain windowing is then usually employed to suppress most of the out-of-band emissions. A common technique is to apply a raised cosine window in time domain. The roll-off factor β is defined as the portion of the total symbol time $T_s = T_U + T_{CP}$ where the roll-off is taking place, as shown in Figure 21. In [Nee00] it is shown that a roll-off factor β = 2.5 % already makes a large improvement in the out of band emissions. Larger roll-off of course improves the spectrum further, however at the cost of smaller delay spread tolerance since the usable part of the symbol gets shorter. The effective guard time is reduced by βT_s.

Choice of windowing will be a trade-off between spectral properties and reduced tolerance against delay spread.
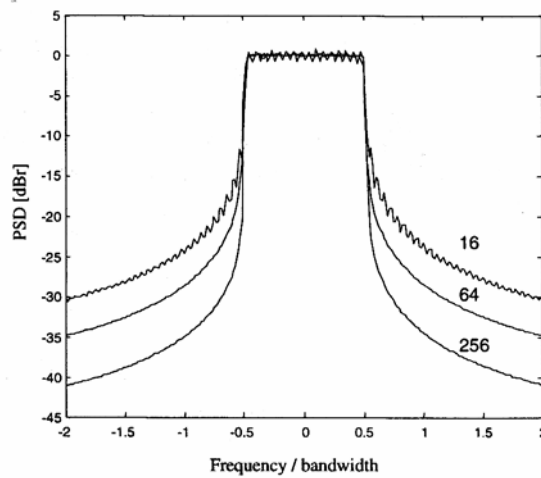

Figure 20   Power spectral density without windowing for 16, 64 and 256 sub-carriers [Nee00]
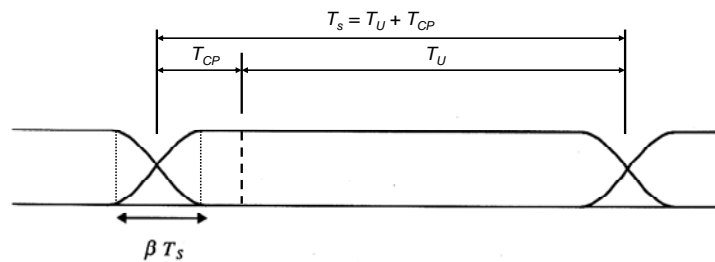

Figure 21   OFDM cyclic extension and windowing

It varies whether windowing is actually used in different systems. In e.g. Evolved UTRA and Mobile WiMAX no filtering is specified, while in the 3GPP2 standardised *Ultra Mobile Broadband* (UMB) a raised cosine filter is defined with a roll-off factor between 2.4 and 2.9 %, dependent on choice of CP length.

3 Multi-user communications – OFDMA

Multi user communications require multiple access techniques. Generally, any of the familiar techniques (TDMA and FDMA) can be employed regardless of the OFDM-nature of the signal. However, the OFDM properties can also be used for multiple access, i.e. *Orthogonal Frequency Division Multiple Access* (OFDMA).

OFDM can be used as a multiple access scheme by allowing simultaneous frequency-separated transmissions to/from multiple mobile terminals as shown in Figure 22.
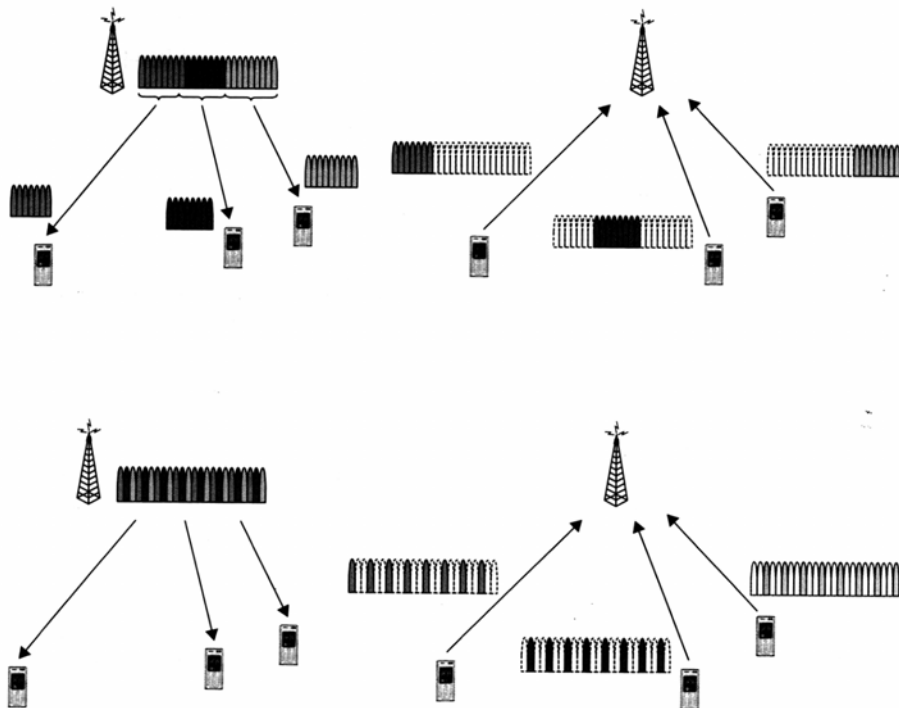

Figure 22   OFDMA principles. Upper: Consecutive channel multiplexing. Lower: Distributed channel multiplexing

3.1 Sub-carrier allocation techniques

The allocation of sub-carriers to the different users can be done in basically two different ways:

- Consecutive (or localized) frequency mapping
- Distributed frequency mapping

3.1.1 Consecutive (localized) frequency mapping

Localized frequency mapping means that all sub-carriers belonging to the link between one user terminal and the base station are allocated in one contiguous block. An example is shown in Figure 23. The major drawback with this method is that it is sensitive to frequency selective fading, see e.g. Figure 15. Whole blocks can be erased.

A variant of localized frequency mapping is shown in Figure 24. In this case, the sub-carriers are localized in equal size blocks, and resources allocated to one user consist of one or more block. In this way, the system becomes more robust to frequency selective fading.
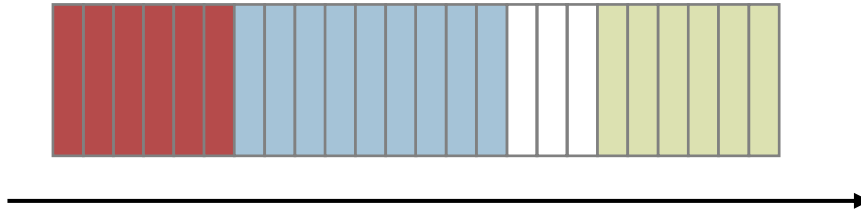

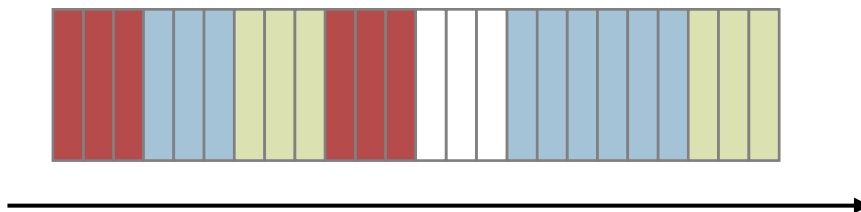*Figure 23   Consecutive frequency mapping*

Figure 24   Blockwise consecutive frequency mapping

For satisfactory performance, localized frequency mapping should be combined with channel dependent scheduling, which is briefly described in section 3.1.3.

In E-UTRA an arbitrary number of sub-blocks of 12 sub-carriers can be allocated on the downlink and scheduled differently every 0.5 ms (see section 4.1.1). In Mobile WiMAX, "Band AMC" is a localized frequency mapping technique (see section 4.2.3).

3.1.2 Distributed frequency mapping

At the opposite end of the scale is the fully distributed mapping in which single sub-carriers belonging to one link are spread across the whole OFDM bandwidth as shown in Figure 25. It fully exploits the channel's frequency diversity but puts stronger demands on frequency synchronization.
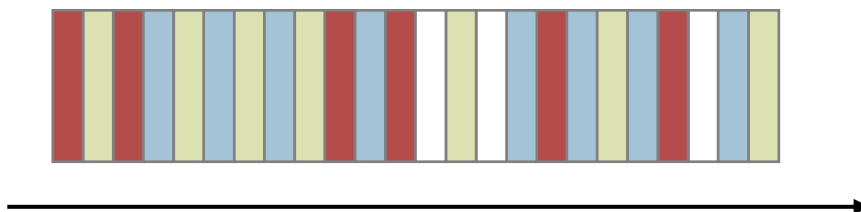

Figure 25   Distributed frequency mapping

Obviously, this method is much more robust to frequency selective fading. A method for re-scheduling resources in the time domain must also be employed.

Distributed mapping is employed in Mobile WiMAX as "FUSC" and "PUSC" (see section 4.2.2). Clusters of 14 sub-carriers are re-scheduled every second OFDM symbol, approximately 0.2 ms. The clusters are spread over the whole OFDM bandwidth and is commonly called diversity sub-channelization. Although it may

seem like a blockwise method as described in the previous section, a detailed examination reveals that this is a true distributed technique.

3.1.3 Channel dependent scheduling

Handling the frequency selective fading is important in OFDM-based systems in order to give satisfactory performance. In OFDMA we have the possibility of using channel estimates to optimize the sub-carrier allocation based on these estimates.

Figure 26 shows how the time-frequency fading is different for two different users due to their different locations [Dahl07]. By obtaining channel estimates often enough, the time-frequency blocks can be re-scheduled to maximize the performance. The example shows how it can be used in E-UTRA.
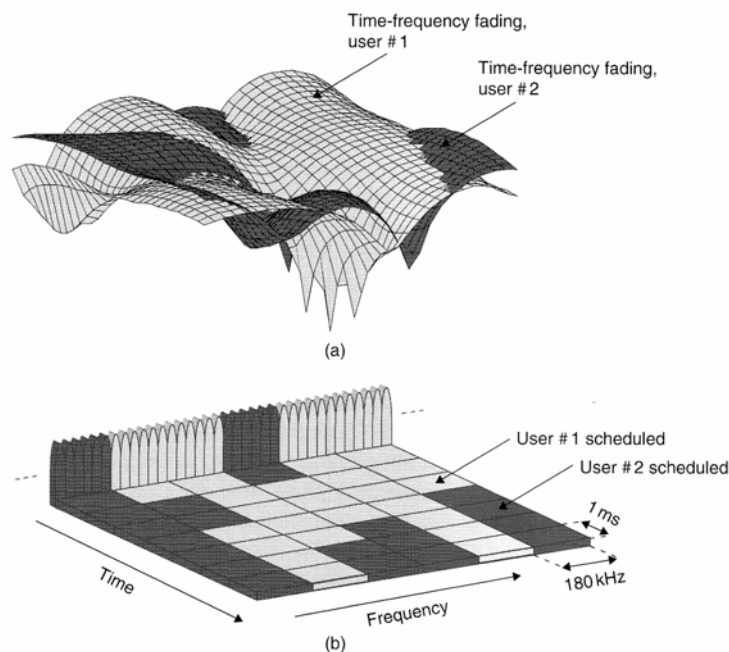

Figure 26   Channel dependent scheduling [Dahl07]

3.2 Synchronization aspects

In *downlink* (DL) all control is located in the base station, including full control of time- and frequency synchronization.

In the *uplink* (UL) in principle the same techniques can be used as for DL, however since the terminals generally have no knowledge of each other, some demands are imposed. The ICI must be avoided or kept at a minimum, and there are two effects which cause deterioration of this. Effect number one is when the orthogonality between sub-carriers belonging to different users is reduced due to imperfect frequency synchronization between the terminals; hence good frequency synchronization is important. Additionally, the timing must be good enough so that ISI is kept within the CP. The second effect is when different mobile terminals are received with significantly different power at the base station. Since perfect orthogonality is practically impossible, strong received sub-carriers may interfere unacceptably on weaker received ones. Consequently a power control on the mobile stations is important.

3.3 DFT-spread OFDMA (SC-FDMA)

In section 2.1.2, we showed that OFDM-signals suffer from a large peak-to-average-power ratio (PAPR) when combining several narrowband carriers. This imposes demands on the power amplifiers of the transmitter to be linear and be operating with a large back-off to avoid harmonic and inter-modulation distortion. In a base station, this is not a major problem, however in the terminal this will lead to higher power consumption and shorter battery life as well as a more expensive unit.

This is why an alternative for the uplink multiple access scheme has been suggested and eventually adopted for 3GPP E-UTRA.

The UL multiple access scheme for 3GPP E-UTRA is called *Single-Carrier Frequency Division Multiple Access* (SC-FDMA), a variant of DFT-spread OFDMA. It is very similar to traditional OFDMA as used in the WiMAX uplink and is based on the same building blocks. The difference is that the resulting signal applied to the transmitter resembles a single-carrier behaviour and consequently a lower PAPR. A short description is given here, while the details are given in the next chapter. The description is mostly based on two papers by Myung et al [Myu06] [Myu07] and by the recently published book by Dahlman et al [Dahl07]. Figure 27 shows the signal chain from transmitter to receiver for both conventional OFDMA and DFT-spread OFDMA.
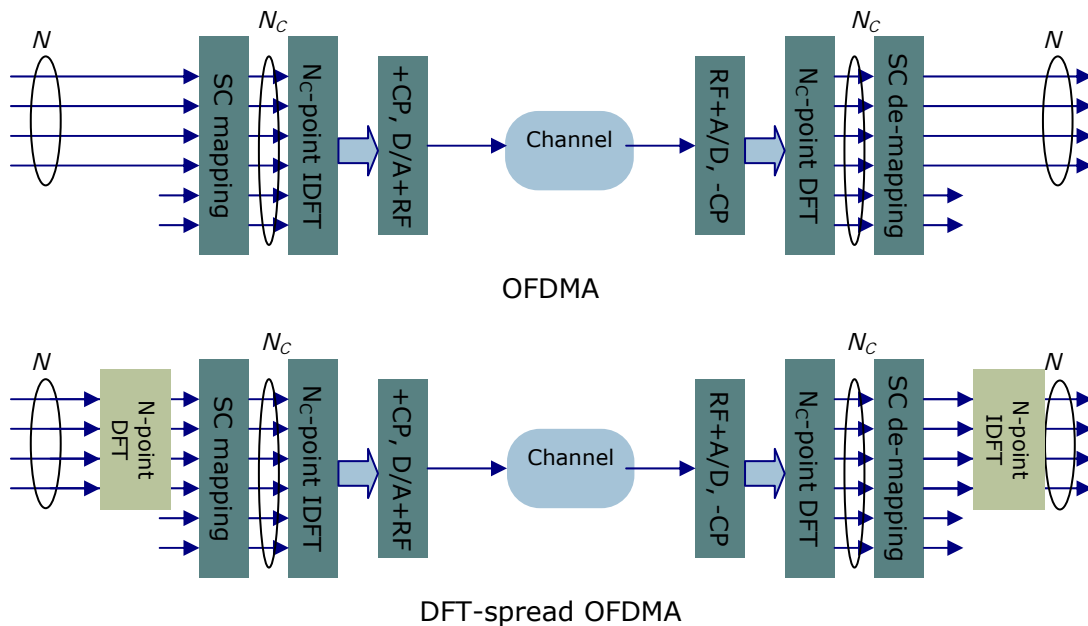

Figure 27   Transmitter and receiver structure of conventional OFDMA and DFT-spread OFDMA

From the figure we see that in DFT-spread OFDMA, the block of input symbols, $\{x_n\}$, on the transmitter is fed through an N-point DFT before the sub-carrier mapping is performed (N is the number of allocated SCs to the specific user). This implies that all (time) symbols are spread on all allocated sub-carriers and all sub-carriers are modulated with a weighted sum of all symbols. The sub-carrier mapping can be both localized and distributed as explained above. When applying the usual Inverse N_C-point DFT after the sub-carrier mapping, new time-domain symbols are generated (N_C is the total number of SCs in the OFDM channel). After adding CP and possible windowing a serial sequence of symbols

is modulated and transmitted, instead of the usual parallel OFDM-scheme. On the receiver, an extra *N*-point IDFT is applied to recreate the original symbols.

The resulting signal can be said to have a "single-carrier" property, which is intuitively "easy" to understand when using localized SC mapping. When distributed SC mapping is used, this is not so obvious. It is shown in [Myu06b] that the reduced PAPR holds for both cases.

Simulations done on different variants of SC-FDMA have been done in [Myu06b] and show that the PAPR is reduced by approximately 2-3 dB for localized mapping compared to conventional OFDMA (see Figure 28)
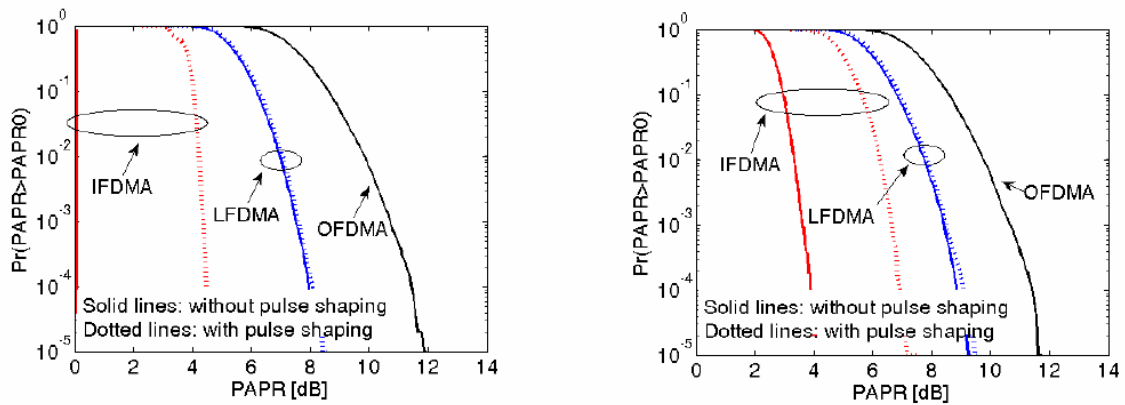

Figure 28   Complementary Cumulative Distribution Functions (CCDF) for the PAPR of Interleaved (distributed) FDMA, Localized FDMA and OFDMA. 256 sub-carriers total (N_C), 64 allocated to user (N). Pulse shaping is with raised cosine roll-off of 50 %. Left: QPSK, Right: 16-QAM [Myu06b]

However, this may only be the upside of SC-FDMA. It is also shown in [Alam07] that the cost associated is 2 to 3 dB performance loss in fading channels in the receiver, see Figure 29. Figure 30 also shows that when performing the DFT-spreading, the PAPR is moved to the frequency domain leading to larger instantaneous out-of band emissions.
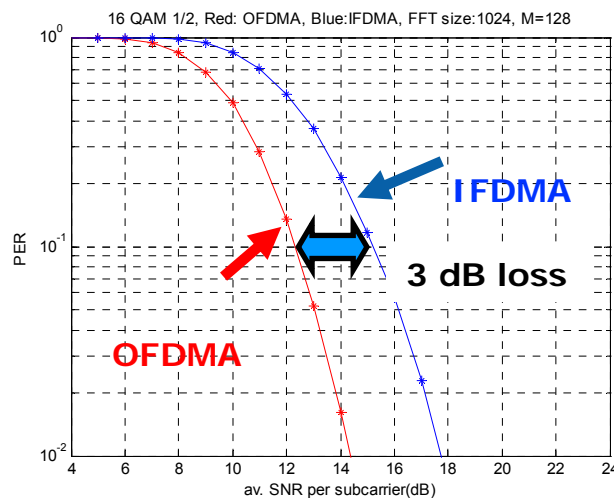

Figure 29   Signal-to-noise ratio (SNR) degradation for IFDMA (DFT-spread OFDMA with distributed mapping) compared to OFDMA [Alam07]
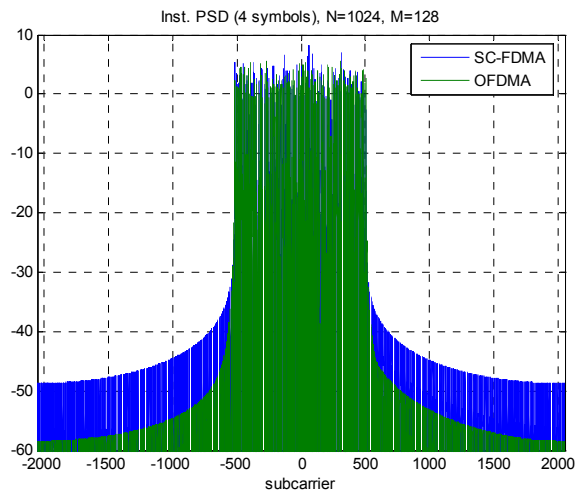
Figure 30   Frequency spectrum of SC-FDMA and OFDMA showing increased out-of-band emissions due to higher PAPR in the frequency domain [Alam07]