3.5 CYCLIC PREFIX AND WINDOWING

Cyclic prefix is a key element of enabling the OFDM signal to operate reliably.

The cyclic prefix acts as a buffer region or guard interval to protect the OFDM signals from intersymbol interference. This can be an issue in some circumstances even with the much lower data rates that are transmitted in the multicarrier OFDM signal.

The basic concept behind the OFDM cyclic prefix is quite straightforward.

The cyclic prefix performs two main functions.

- The cyclic prefix provides a guard interval to eliminate intersymbol interference from the previous symbol.
- It repeats the end of the symbol so the linear convolution of a frequency- selective multipath channel can be modeled as circular convolution, which in turn may transform to the frequency domain via a discrete Fourier transform. This approach accommodates simple frequency domain processing, such as channel estimation and equalization.

The cyclic prefix is created so that each OFDM symbol is preceded by a copy of the end part of that same symbol.

Different OFDM cyclic prefix lengths are available in various systems.

For example within LTE a normal length and an extended length are available and after release a third extended length is also included, although not normally used.

Advantages of Cyclic prefix

- Provides robustness: The addition of the cyclic prefix adds robustness to the OFDM signal. The data that is retransmitted can be used if required.
- Reduces inter-symbol interference: The guard interval introduced by the cyclic prefix enables the effects of inter-symbol interference to be reduced.

Disadvantages

- Reduces data capacity: As the cyclic prefix re-transmits data that is already being transmitted, it takes up system capacity and reduces the overall data rate.

The use of a cyclic prefix is standard within OFDM and it enables the performance to be maintained even under conditions when levels of reflections and multipath propagation are high.

Cyclic Prefix is referred as the Guard time and cyclic extension

To eliminate inter symbol interference completely, a guard time is introduced for each OFDM symbol. The guard time is chosen larger than the expected delay spread, such that multipath components from one symbol cannot interfere with the next symbol. The guard time could consist of no signal at all.

When an OFDM receiver tries to demodulate the first subcarrier, it will encounter some interference from the second subcarrier, because within the FFT interval, there is no integer number of cycles difference between subcarrier I and 2.

At the same time, there will be crosstalk from the first to the second subcarrier for the same reason.

To eliminate ICI, the OFDM symbol is cyclically extended in the guard time, This ensures that delayed replicas of the OFDM symbol always have an integer number of cycles within the FFT interval, as long as the delay is smaller than the guard time. As a result, multipath signals with delays smaller than the guard time cannot cause ICI.

Hence, the subcarriers are not orthogonal anymore, but the interference is still small enough to get a reasonable received constellation.

WINDOWING

In OFDM signals , sharp phase transitions caused by the modulation can be seen at the symbol boundaries. An OFDM signal consists of a number of unfiltered QAM subcarriers. As a result, the out-of-band spectrum decreases rather slowly, according to a sine function. For larger number of subcarriers, the spectrum goes down more rapidly in the beginning, which is caused by the fact that the side lobes are closer together. The spectrum for 256 subcarriers has a relatively large -40-dB bandwidth that is almost four times the -3-dB bandwidth.

To make the spectrum go down more rapidly, windowing can be applied to the individual OFDM symbols. Windowing an OFDM symbol makes the amplitude go smoothly to zero at the symbol boundaries.

A commonly used window type is the raised cosine window, which is defined as

$$w(t)=\begin{cases} 0.5+0.5\cos(\pi+t\pi/(\beta T_s)) & 0 \le t \le \beta T_s \\ 1.0 & \beta T_s \le t \le T_s \\ 0.5+0.5\cos((t-T_s)\pi/(\beta T_s)) & T_s \le t \le (1+\beta)T_s \end{cases}$$

Here, Ts, is the symbol interval, which is shorter than the total symbol duration because we allow adjacent symbols to partially overlap in the roll-off region.

In practice, the OFDM signal is generated as follows:

First, Nc input QAM values are padded with zeros to get N input samples that are used to calculate an IFFT. Then, the last Tprefix, fix samples of the IFFT output are inserted at the start of the OFDM symbol, and the first Tpostfix samples are appended at the end. The OFDM symbol is then multiplied by a raised cosine window w(t) to more quickly reduce the power of out-of-band subcarriers.

The OFDM symbol is then added to the output of the previous OFDM symbol with a delay of Ts, such that there is an overlap region of βTs,, where β is the roll off factor of the raised cosine window.

PEAK-TO-AVERAGE POWER RATIO

One of the major problems of OFDM is that the peak amplitude of the emitted signal can be considerably higher than the average amplitude. This Peak-to-Average Power Ratio (PAPR) issue originates from the fact that an OFDM signal is the superposition of N sinusoidal signals on different subcarriers.

On average the emitted power is linearly proportional to N. However, sometimes, the signals on the subcarriers add up constructively, so that the amplitude of the signal is proportional to *N*, and the power thus goes with N^2.

If the number of subcarriers is large, we can invoke the central limit theorem to show that the distribution of the amplitudes of in-phase components is Gaussian, with a standard deviation $\sigma = 1/\sqrt{2}$ (and similarly for the quadrature components) such that mean power is unity. Since both in-phase and quadrature components are Gaussian, the absolute amplitude is Rayleigh distributed.

There are three main methods to deal with the Peak-to-Average Power Ratio (PAPR):

1. Put a power amplifier into the transmitter that can amplify linearly up to the possible peak value of the transmit signal. This is usually not practical, as it requires expensive and power-consuming class-A amplifiers. The larger the number of subcarriers *N*, the more difficult this solution becomes.

2. Use a nonlinear amplifier, and accept the fact that amplifier characteristics will lead to distortions in the output signal. Those nonlinear distortions destroy orthogonality between subcarriers, and also lead to increased out-of-band emissions (spectral regrowth – similar to third-order intermodulation products – such that the power emitted outside the nominal band is increased).

The first effect increases the BER of the desired signal (see Figure 3.4.3), while the latter effect causes interference to other users and thus decreases the cellular capacity of an OFDM system (see Figure 3.4.4). This means that in order to have constant adjacent channel interference we can trade off power amplifier performance against spectral efficiency (note that increased carrier separation decreases spectral efficiency).

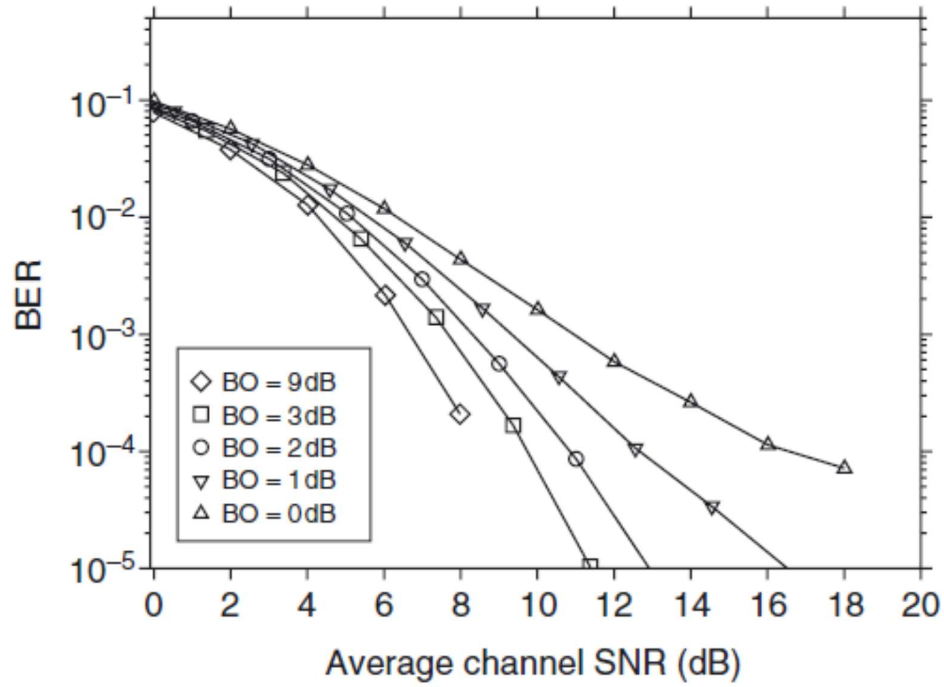

Fig 3.4.3 Bit error rate as a function of the signal-to-noise ratio, for different backoff levels of the transmit amplifier.

[Source : "Wireless communications" by Andreas F.Molisch,Page-430]

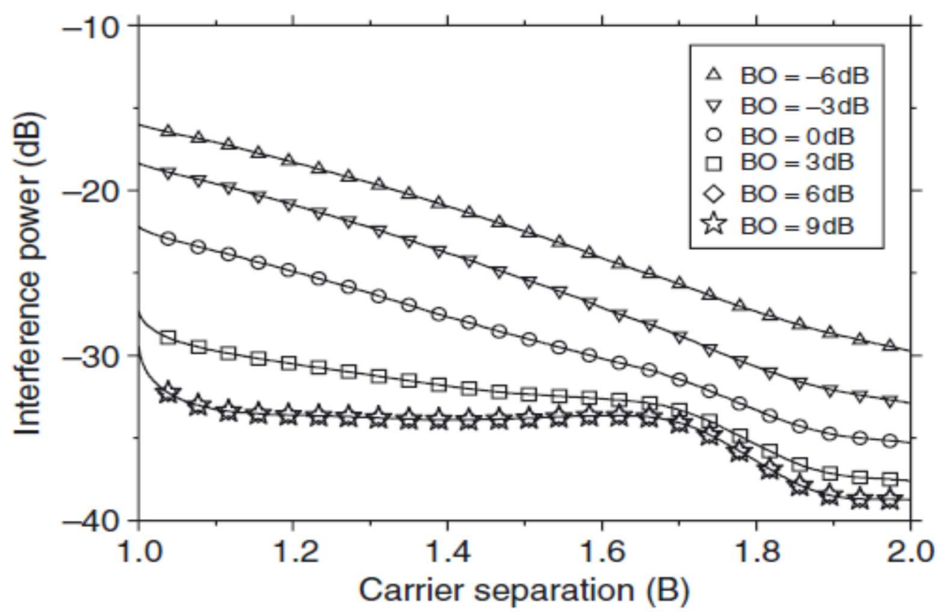

Fig 3.4.4 Interference power to adjacent bands (OFDM users), as a function of carrier separation

[Source : "Wireless communications" by Andreas F.Molisch,Page-430]

3. Use PAR reduction techniques.

1.Coding for PAR reduction: Under normal circumstances, each OFDM symbol can represent one of $2N$ codewords (assuming BPSK modulation). Now, of these codewords only a subset of size $2K$ is acceptable in the sense that its PAR is lower than a given threshold. Both the transmitter and the receiver know the mapping between a bit combination of length K, and the codeword of length N that is chosen to represent it, and which has an admissible PAR.

The transmission scheme is thus the following: (i) parse the incoming bitstream into blocks of length K; (ii) select the associated codeword of length N; (iii) transmit this codeword via the OFDM modulator.The coding scheme can guarantee a certain value for the PAR.

2.Correction by multiplicative function: Here we multiply the OFDM signal by a time-dependent function whenever the peak value is very high. The simplest example for such an approach is the clipping we mentioned in the previous subsection: if the signal attains a level sk >A0, it is multiplied by a factor A0/sk. In other words, the transmit signal becomes

$$\hat{s}(t) = s(t)\left[1 - \sum_k \max\left(0, \frac{|s_k| - A_0}{|s_k|}\right)\right]$$

A less radical method is to multiply the signal by a Gaussian function centered at times when the level exceeds the threshold:

$$\hat{s}(t) = s(t)\left[1 - \sum_n \max\left(0, \frac{|s_k| - A_0}{|s_k|}\right)\exp\left(-\frac{t^2}{2\sigma_t^2}\right)\right]$$

Multiplication by a Gaussian function of variance $\sigma_t{}^2$ in the time domain implies convolution with a Gaussian function in the frequency domain with variance $\sigma_f{}^2 = 1/(2\pi\sigma_t{}^2)$. Thus, the amount of out-of-band interference can be influenced by the judicious choice of $\sigma_t{}^2$.