Name of Faculty: Prof Arun KumarPatel

Department : EC

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UNIT: II Orthogonal Frequency Division Multiplexing (OFDM)

UNIT 2

Orthogonal Frequency Division Multiplexing (OFDM)

Introduction, principle of OFDM, implementation of transceivers, frequency-selective channels, channel estimation, peak to average power ratio, inter carrier interference, adaptive modulation and capacity, multiple access, multi carrier code division multiple access, single carrier modulation with frequency-domain equalization.

Principle of OFDM

OFDM is a special form of multicarrier (MC).OFDM reduce the required bandwidth but keeping the modulated signals orthogonal so they do not interfere with each other. It is based on the principal of frequency division multiplexing (FDM), which is a technique that uses multiple frequencies to transmit multiple signals in parallel simultaneously. Each signal has its own frequency range (subcarrier), which is then modulated by data. Each subcarrier is separated by a guard band to ensure that they do not overlap. This subcarrier is then demodulated at the receiver by using filters to separate the bands. OFDM is a combination of modulation and multiplexing.

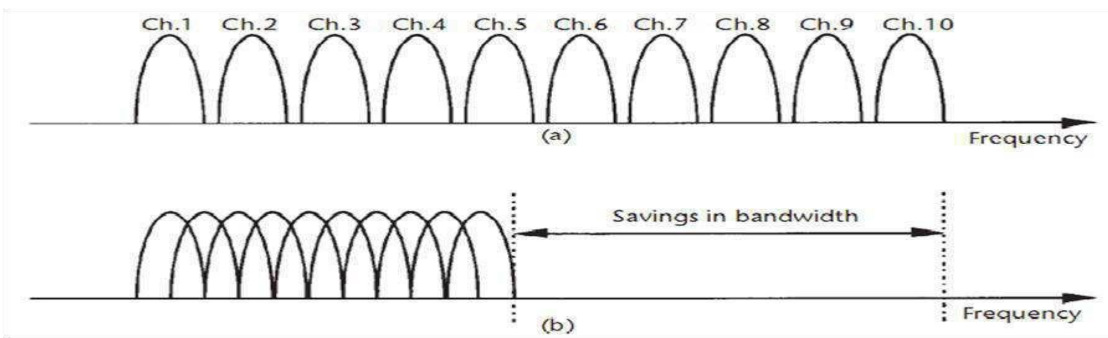

Figure 2.1 Concept of the OFDM signal (a) conventional multicarrier technique (b) orthogonal multicarrier modulation technique.

OFDM is simply defined as a form of multicarrier modulation where the carrier spacing is carefully selected so that each sub carrier is orthogonal to the other sub carriers. Two signals are orthogonal if their dot product is zero That is, if you take two signals multiply them together and if their integral over an interval is zero, then two signals are orthogonal in that interval. Orthogonality can be obtained by carefully selecting carrier spacing, such as letting the carrier spacing be equal to the reciprocal of the useful symbol period. If the sub carriers are orthogonal then the spectrum of each carrier at the center frequency of each of the other carriers in the system is a null. This results in no interference between the carriers, allowing them to be spaced as close as theoretically possible.

OFDM Generation and Reception

The block diagram of OFDM transceiver is shown in figure. The transmitter section converts digital data to be transmitted, into a mapping of subcarrier amplitude and phase. It then transforms this spectral representation of the data into the time domain using an Inverse Fast Fourier Transform (IFFT). In order to transmit the OFDM signal the calculated time domain signal is then mixed up to the required frequency.

The receiver performs the reverse operation of the transmitter, mixing the RF signal to base band for processing, then using a Fast Fourier Transform (FFT) to analyze the signal in the frequency domain. The amplitude and phase of the subcarriers is then picked out and converted back to digital data.
The IFFT and the FFT are complementary function and the most appropriate term depends on whether the signal is being received or generated. In cases where the signal is independent of this distinction then the term FFT and IFFT is used interchangeably.

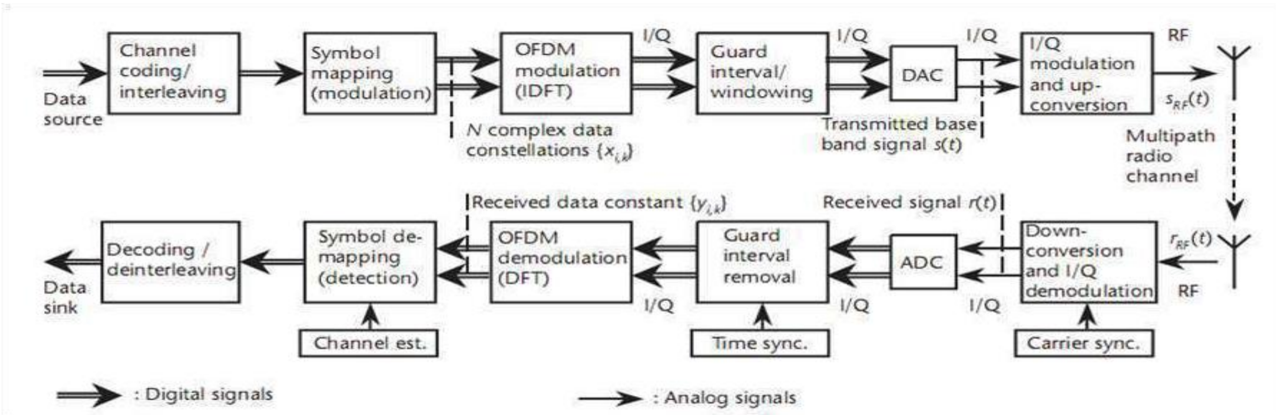

Figure 2.2 Block diagram of OFDM transceiver

Serial to Parallel Conversion

Data to be transmitted is typically in the form of a serial data stream. In OFDM, each symbol typically transmits 40-4000 bits, and so a serial to parallel conversion stage is needed to convert the input serial bit stream to the data to be transmitted in each OFDM symbol. The data allocated to each symbol depends on the modulation scheme used and the number of subcarriers. For example, for a subcarrier modulation of 16-QAM each subcarrier carries 4 bits of data, and so for a transmission using 100 subcarriers the number of bits per symbol would be 400.

At the receiver the reverse process takes place, with the data from the subcarriers being converted back to the original serial data stream. When an OFDM transmission occurs in a multipath radio environment, frequency selective fading can result in groups of subcarriers being heavily attenuated, which in turn can result in bit errors. These nulls in the frequency response of the channel can cause the information sent in neighboring carriers to be destroyed, resulting in a clustering of the bit errors in each symbol. Most Forward Error Correction (FEC) schemes tend to work more effectively if the errors are spread evenly, rather than in large clusters, and so to improve the performance most systems employ data scrambling as part of the serial to parallel conversion stage. This is implemented by randomizing the subcarrier allocation of each sequential data bit. At the receiver the reverse scrambling is used to decode the signal. This restores the original sequencing of the data bits, but spreads clusters of bit errors so that they are approximately uniformly distributed in time. This randomization of the location of the bit errors improves the performance of the FEC and the system as a whole.

- **Modulation & Demodulation**

OFDM transmitter maps the message bits into a sequence of PSK or QAM symbols which will be subsequently converted into N parallel streams. Each of N symbols from serial to parallel (S/P) conversion is carried out by the different subcarrier.

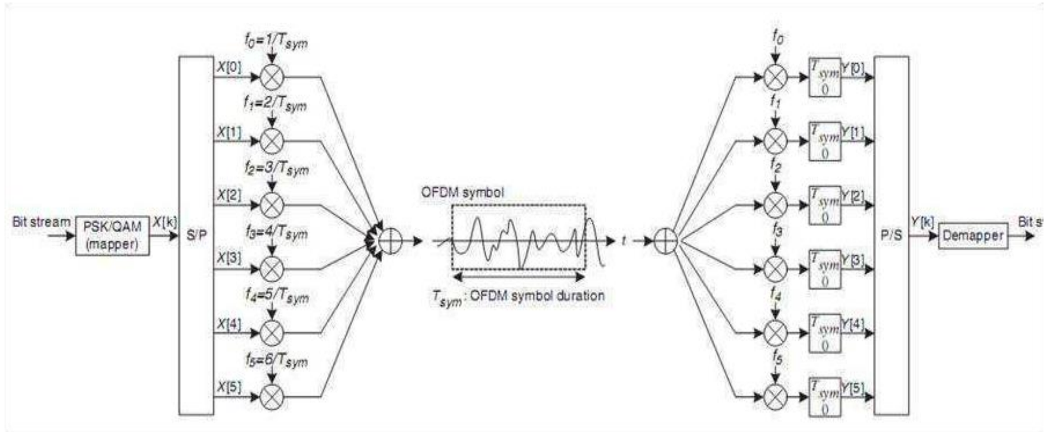

Figure 2.3 OFDM modulation and demodulation N=6.

Figure shows the basic OFDM modulation and demodulation, the frequency domain symbol X[k] modulates the subcarrier with a frequency of $f_k = k/T_{sys}$ for N =6 (i.e., k = 0, 1, 2..., 5) while it can be demodulated by using the Orthogonality among the subcarriers in the receiver.

- **Frequency to Time Domain Conversion (IFFT)**

After the subcarrier modulation stage each of the data subcarriers is set to amplitude and phase based on the data being sent and the modulation scheme all unused subcarriers are set to zero. This sets up the OFDM signal in the frequency domain. An IFFT is then used to convert this signal to the time domain, allowing it to be transmitted. In the frequency domain, before applying the IFFT, each of the discrete samples of the IFFT corresponds to an individual subcarrier. Most of the subcarriers are modulated with data. The outer subcarriers are un- modulated and set to zero amplitude. These zero subcarriers provide a frequency guard band before the Nyquist frequency and effectively act as an interpolation of the signal and allows for a realistic roll off in the analog anti-aliasing reconstruction filters.

- **Guard Period**

For a given system bandwidth the symbol rate for an OFDM signal is much lower than a single carrier transmission scheme. For example for a single carrier BPSK modulation, the symbol rate corresponds to the bit rate of the transmission. However for OFDM the system bandwidth is broken up into Nc subcarriers, resulting in a symbol rate that is Nc times lower than the single carrier transmission. This low symbol rate makes OFDM naturally resistant to effects of Inter- symbol Interference (ISI) caused by multipath propagation.

The effect of ISI on an OFDM signal can be further improved by the addition of a guard period to the start of each symbol. This guard period is a cyclic copy that extends the length of the symbol waveform. Each subcarrier, in the data section of the symbol has an integer number of cycles i.e. the OFDM symbol with no guard period added, which is equal to the length of the IFFT size used to generate the signal. Due to placing copies of the symbol end to end results in a continuous signal, with no discontinuities at the joins. Thus by copying the end of a symbol and appending this to the start results in a longer symbol time. In addition to protecting the OFDM from ISI, the guard period also provides protection against time offset errors in the receiver. Figure shows the insertion of a guard period.

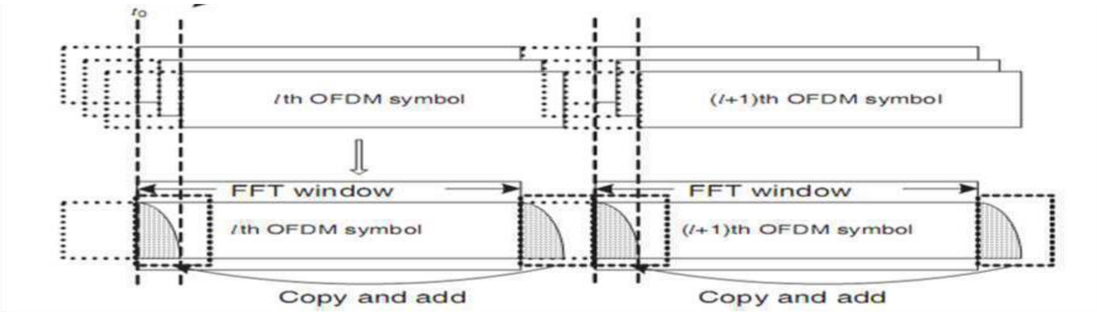

Figure 2.4 Addition of a guard period to an OFDM signal

The OFDM guard interval can be inserted in two different ways. One is the zero padding (ZP) that pads the guard interval with zeros. The other is the cyclic extension of the OFDM symbol with CP (cyclic prefix) or CS (cyclic suffix). CP is to extend the OFDM symbol by copying the last samples of the OFDM symbol into its front as shown in figure.

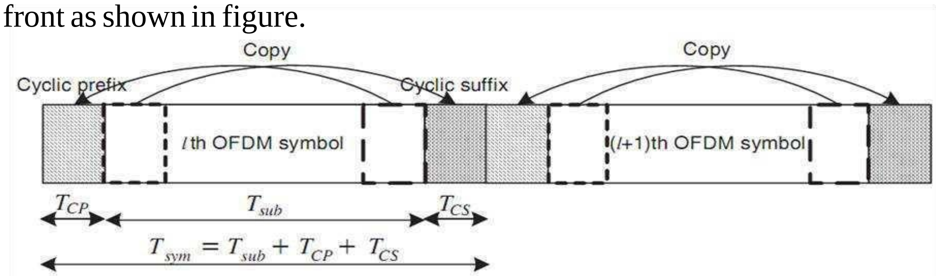

Figure 2.5 OFDM symbol with both CP and CS.

We may insert zero into the guard interval. This particular approach is adopted by multiband OFDM (MB-OFDM) in an Ultra Wide-band (UWB) system. Figure show OFDM symbols with ZP. Even with the length of ZP longer than the maximum delay of the multipath channel, a small STO causes the OFDM symbol of an effective duration to have a discontinuity within the FFT window and therefore, the guard interval part of the next OFDM symbol is copied and added into the head part of the current symbol to prevent ICI.

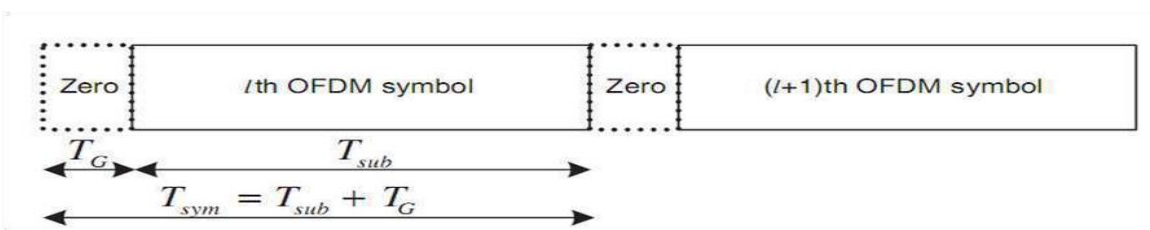

Figure 2.6 OFDM symbol with Zero padding.

Channel Estimation

As OFDM operation of systems requires an estimate of the channel transfer function or the channel impulse response. As OFDM is operated with a number of parallel narrowband subcarriers, it is conscious to estimate the channel in the frequency domain. Following channel estimation techniques are used

(i) Pilot symbols, which are mainly suitable for an initial estimate of the channel

(ii) Scattered pilot tones, which help to track changes in channels over time

(iii) Eigen-value decomposition based methods, which can be used to reduce the complexity of the first two methods.

- Pilot-Symbol-Based Methods

The most straightforward channel estimation in OFDM is when we have a dedicated pilot symbol containing only known data in other words, the data on each of the subcarriers is known. This approach is appropriate for initial acquisition of the channel, at the beginning of a transmission burst. The simplest channel estimate is then obtained by estimating the channel on each subcarrier separately.

- Methods Based on Scattered Pilots

After obtaining an initial estimate of the channel, we need to track changes in the channel as it evolves with time. In this case we would like to do two things:

(i) Reduce the number of known bits in an OFDM symbol ,this improves spectral efficiency.

(ii) Exploit the time correlation of the channel – i.e., the fact that the channel changes only slowly in time.

An attractive way of tracking the channel is to use pilot symbols scattered in the OFDM time frequency grid as illustrated in Figure, where pilots are spaced by N_f subcarriers and N_t OFDM symbols.

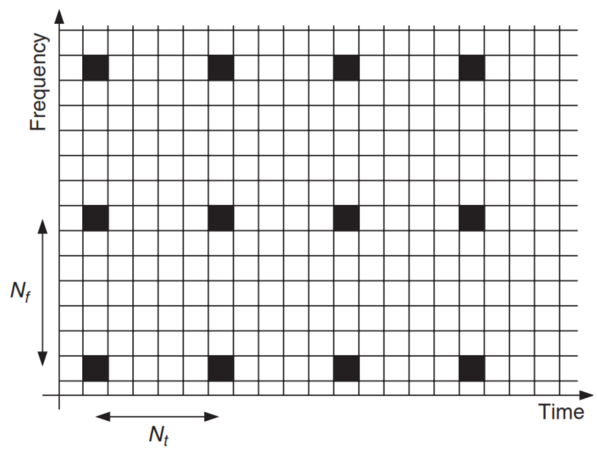

Figure 2.7 Scattered pilots in the orthogonal-frequency-division-multiplexing time frequency grid

- Methods Based in Eigen Decompositions

The structure of OFDM allows for efficient channel estimator structures. We know that the channel impulse response is short compared with the OFDM symbol length in any well designed system. This fact can be used to reduce the dimensionality of the estimation problem. In essence, when using the LMMSE estimator, we would like to use the statistical properties of the channel to perform the matrix multiplication more efficiently. This can be done using the theory of optimal rank reduction from estimation theory, where an Eigen Value Decomposition (EVD) is

$$hh = \wedge *$$

The dimension of this space is approximately N_{cp}+1 i.e., one more than the number of samples in the cyclic prefix. We can therefore expect that, after the first N_{cp}+1 diagonal element in $\wedge$, the magnitude should decrease rapidly.

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 Ratio (PAR) 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. We can thus anticipate the (worst case) power PAR to increase linearly with the number of subcarriers. Following Peak-to-Average Ratio Reduction Techniques are used

1. Coding for PAR reduction
2. Phase adjustments
3. Correction by multiplicative function
4. Correction by additive function

Inter Carrier Interference

The cyclic prefix provides an excellent way of ensuring orthogonality of the carriers in a delay dispersive environment in other words; there is no ICI due to frequency selectivity of the channel. However, wireless propagation channels are also time varying. Time selectivity has two important consequences for an OFDM system:

(i) It leads to random Frequency Modulation which can cause errors especially on subcarriers that are in a fading dip

(ii) It creates ICI. A Doppler shift of one subcarrier can cause ICI in many adjacent.

Delay dispersion can be another source of ICI, namely if the cyclic prefix is shorter than the maximum excess delay of the channel. This situation can arise for various reasons.

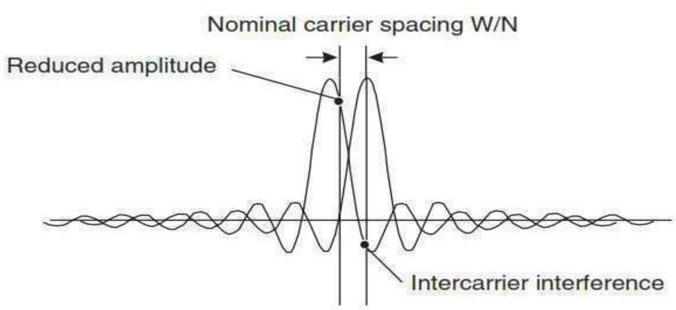

Figure 2.8 Inter carrier interference due to frequency offset.

Adaptive Modulation and Capacity

Adaptive modulation changes the coding scheme and modulation method depending on channel state information choosing it in such a way that it always "pushes the limit" of what the channel can transmit. In OFDM, modulation and coding can be chosen differently for each subcarrier, and it can also change with time. We thus not only accept the fact that the channel shows strong variations but even exploit this fact. On subcarriers with good SNR, transmission is done at a higher rate than on subcarriers with low SNR. In other words, such an adaptive modulation selects a modulation scheme and code rate according to the channel quality of a specific subcarrier.

Multicarrier Code Division Multiple Access

Multi Carrier CDMA (MC-CDMA) spreads information from each data symbol over all tones of an OFDM symbol. At first glance, it is paradoxical to combine CDMA, which tries to spread a signal over a very large bandwidth, with multicarrier schemes, which try to signal over a very narrowband channel. But we will see in the following that the two methods can actually be combined very efficiently. We have mentioned repeatedly that un-coded OFDM has poor performance, because it is dominated by the high error rate of subcarriers that are in fading dips. Coding improves the situation, but in many cases a low coding rate i.e., high redundancy is not desirable. We thus need to find an alternative way of exploiting the frequency diversity of the channel. By spreading a modulation symbol over many tones, MC-CDMA becomes less sensitive to fading on one specific tone.

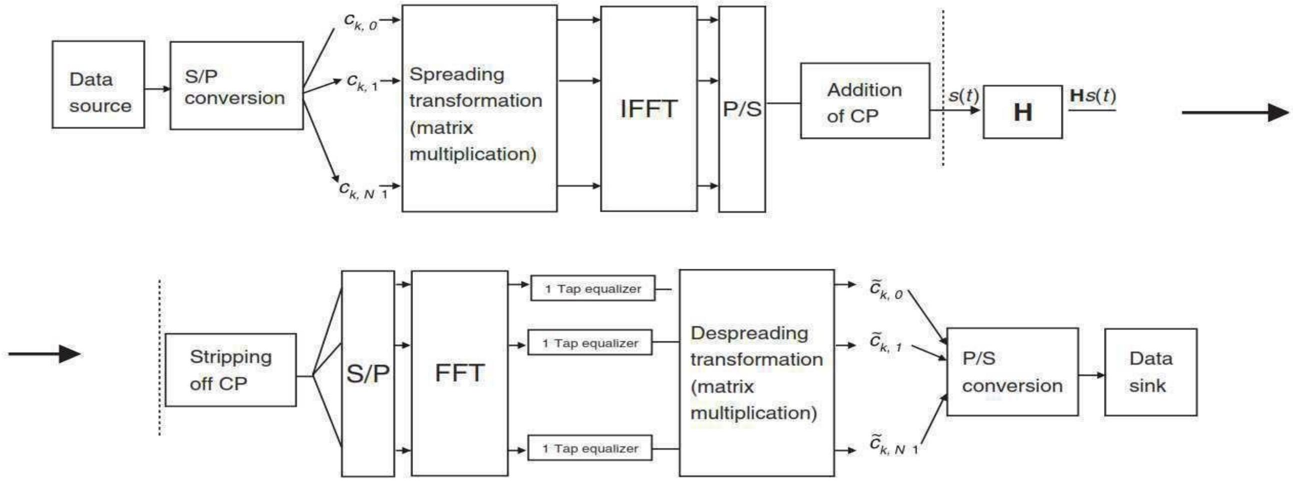

Figure 2.9 Block diagram of a multicarrier code-division-multiple-access transceiver.

Single-Carrier Modulation with Frequency Domain Equalization

A special case of MC-CDMA occurs when the unitary transformation matrix P is chosen to be the FFT matrix. In such a case, multiplication by the spreading matrix and the IFFT inherent in the OFDM implementation cancel out. In other words, the transmit sequence that is transmitted over the channel is the original data sequence plus a cyclic prefix that is just a prep ending of a few data symbols at the beginning of each data block. This just seems like a rather contrived way of describing the single-carrier system. However, the big difference here lies in the existence of the cyclic prefix, as well as in how the signal is processed at the receiver. After stripping off the cyclic prefix, the signal is transformed by an FFT into the frequency domain. Due to the cyclic prefix, there are no residual effects of ISI or ICI. Then, the receiver performs equalization on each subcarrier and finally transforms the signal back into the time domain via an IFFT. The receiver thus performs equalization in the frequency domain. Since FFTs or IFFTs can be implemented efficiently, the computational effort (per bit) for equalization goes only like $\log_2(N)$.

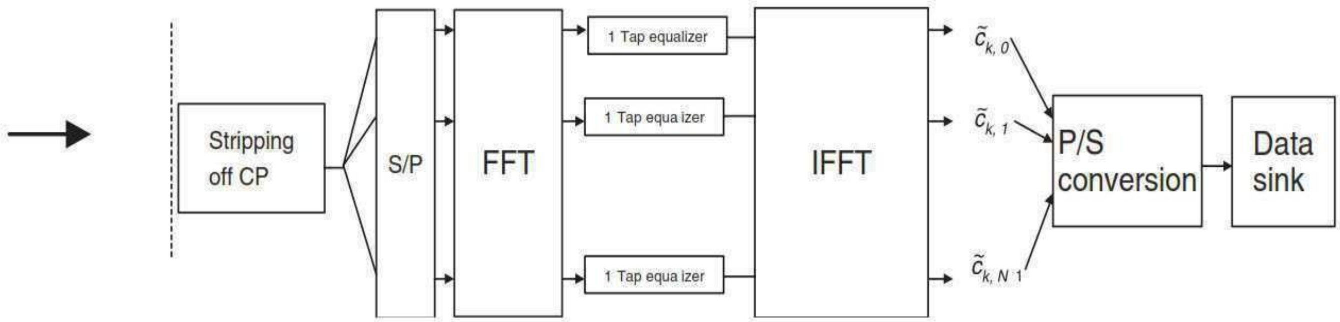

Figure 2.10 Block diagram of a single-carrier frequency domain equalization receiver.