2-1 Introduction to MIMO-OFDM systems

With the rapid growth in technology, the demand for flexible high data-rate services has also increased. The performance of high data rates communication systems is limited by frequency selective multipath fading which results in inter symbol interference (ISI) . In the wireless channels, impairments such as fading, shadowing and interferences due to multiple user access highly degrade the system performance Multicarrier modulation (MCM) is a solution that overcomes these problems in wireless channels It is the technique of transmitting data that divides the serial high data rate streams into a large number of low data rate parallel data streams [2].

Orthogonal Frequency Division Multiplexing (OFDM) is a kind of multi-carrier modulation, which divides the available spectrum into a number of parallel subcarriers and each subcarrier is then modulated by a low rate data stream at different carrier frequency. The conventional OFDM system makes use of IFFT and FFT for multiplexing the signals and reduces the complexity at both transmitter and receiver [3]. OFDM is comprised of a blend of modulation and multiplexing. The original data signal is split into many independent signals, each of which is modulated at a different frequency and then these independent signals are multiplexed to create an OFDM carrier. As all the subcarriers are orthogonal to each other, they can be transmitted simultaneously over the same bandwidth without any interference which is an important advantage of OFDM [3].

OFDM makes the high speed data streams robust against the radio channel impairments OFDM is an efficient technique to handle large data rates in the multipath fading environment which causes ISI. With the help of OFDM, a large number of overlapping narrowband subcarriers, which are orthogonal to each other, are transmitted parallel within the available transmission bandwidth. Thus in OFDM the available spectrum is utilized efficiently

The communication systems and communication networks of the future will fundamentally improve the way people communicate. One among the services expected to have major impact in the future include wireless communication that will permit mobile telephony and data transfer anywhere on the planet . Delivering and receiving these services to the large and rapidly growing commercial markets has created new technological challenge in signal design, modulation, detection, and signal processing For wireless communication systems, limited bandwidth allocations coupled with a potentially large pool of users restrict the bandwidth availability to the users [4].

The success of wirelesses communication systems thus depends heavily on the development of bandwidth efficient data transmission schemes. Wireless multicarrier modulation (MCM-OFDM) is a technique of transmitting data by dividing the input data stream into parallel sub streams that are each modulated and multiplexed onto the channel at different carrier frequencies Wavelet transform is a tool for studying signals in the joint time-frequency domains. Which is capable of providing the time and frequency information simultaneously, thus giving a time-frequency representation of the signal. Wavelets are known to have compact support (localization) both in time and frequency domain, and possess better orthogonality Wavelet-based OFDM has gained popularity in the literature recently. Due to very high spectral containment properties of wavelets, wavelet OFDM can better combat narrowband interference and is inherently more robust with respect to intercarrier interference (ICI) than traditional FFT realization traditionally [4].

Orthogonal frequency division multiplexing (OFDM) is implemented using fast Fourier transforms (FFT). This transform however has the drawback that uses a rectangular window which creates rather high sidelobes Moreover the pulse shaping function used to modulate each subcarrier extends to infinity in the frequency domain. This leads to high interference and lower performance levels. Intercarrier interference (ICI) and intersymbol interference (ISI) can be avoided by adding a cyclic prefix (CP) to the head of OFDM symbol [5].

Adding CP reduces the spectrum efficiency. The Discrete wavelet modulation (DWT) system has a higher spectral efficiency while providing robustness with regard to inter-channel interference than the conventional OFDM system, because of low out-of-band energy (low sidelobes). Moreover DWT is able to decompose T-F plane flexibly by arranging filter bank (FB) constructions DWT system does not require CP thereby enhancing the spectrum efficiency. According to the IEEE broadband wireless standard IEEE 802.16n avoiding CP gives wavelet OFDM an advantage of roughly 20% in bandwidth efficiency. Moreover as pilot tones are not necessary for wavelet based OFDM system, they perform better in comparison to existing OFDM systems like IEEE802.11n or Hyper LAN, where 4 out of 52 sub-bands are used for pilots[5].

This gives wavelet based OFDM system another 8% advantage over typical OFDM implementations We propose an OFDM based on discrete wavelet transform (DWT) inherit all the advantages of DWT system [6].

2-2 structure of MIMO-OFDM systems

In high-speed wireless communication, combining MIMO and OFDM technology OFDM can be applied to transform frequency-selective MIMO channel into parallel flat MIMO channel, reducing the complexity of the receiver, through multipath fading environment can also achieve high data rate robust transmission. Therefore, MIMO-OFDM systems obtain diversity gain and coding gain by space-time coding, at the same time, the OFDM system can be realized with simple structure. Therefore, MIMO-OFDM system has become a welcome proposal for 4G mobile communication systems. The basic structure of MIMO OFDM system model is shown in figure (2-1) below [3].

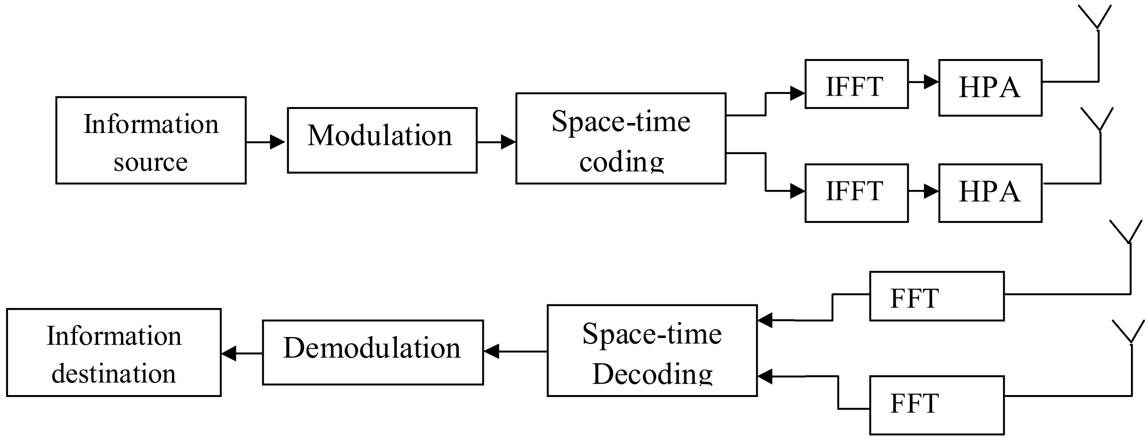


Figure (2-1) basic structure of MIMO OFDM system

2-2-1 MIMO technique

While MIMO techniques can bring huge capacity gains to wireless systems, it is in general difficult to implement the same number of antenna at the mobile receivers as at the base stations. Most mobile stations will still have only a single antenna due to their size and cost constraints. In such a scenario, we can still explore the potential spatial multiplexing gain offered by multiple antenna at the base station through the simultaneous transmission to multiple or single antenna receivers. The resulting multiuser MIMO system, as illustrated in Figure has received a significant amount of research interest. In particular [3]

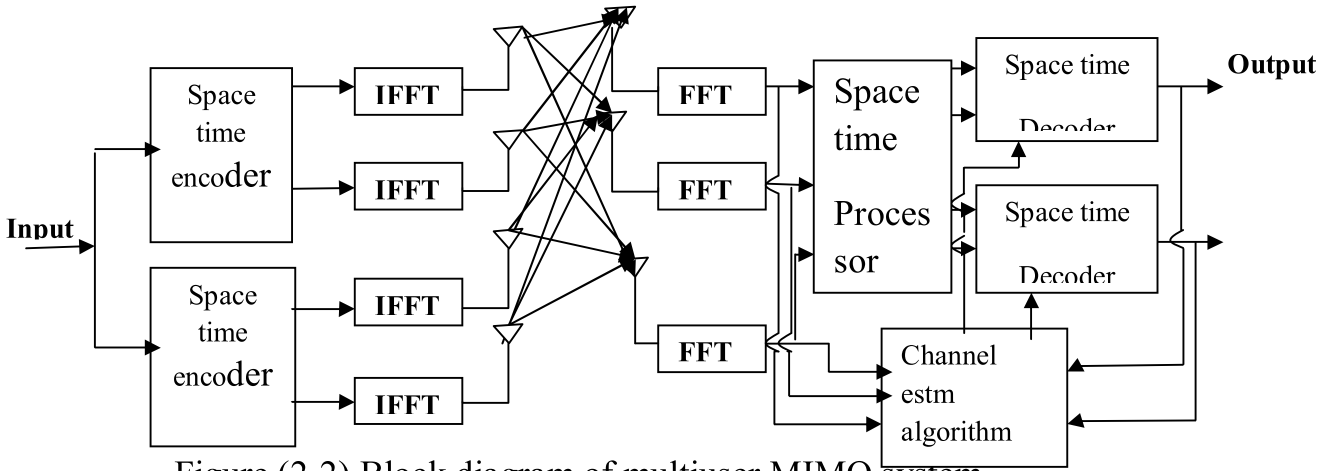
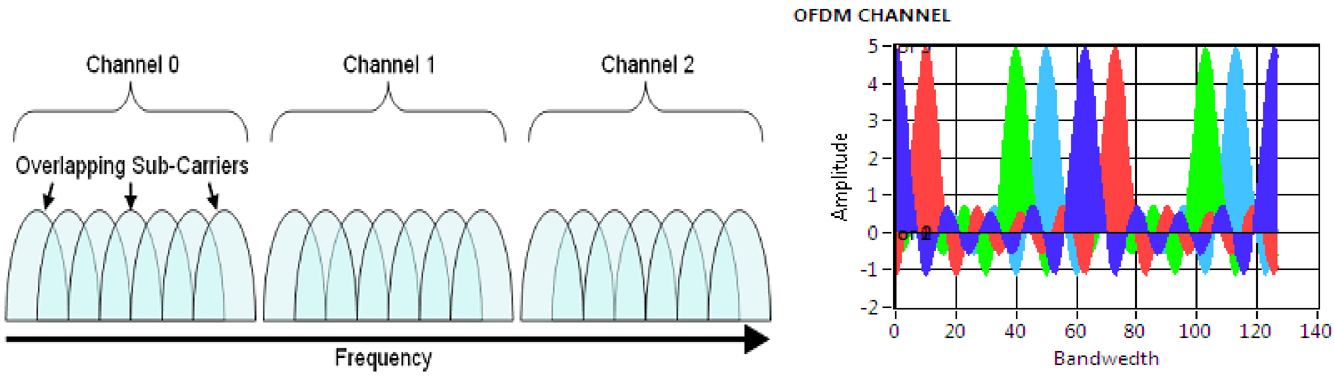


Figure (2-2) Block diagram of multiuser MIMO system

2-2-2 OFDM system

OFDM is a subset of frequency division multiplexing in which a single channel utilizes multiple sub-carriers on adjacent frequencies. In addition the sub-carriers in an OFDM system are overlapping to maximize spectral efficiency. Ordinarily overlapping adjacent channels can interfere with one another. However sub-carriers in an OFDM system are precisely orthogonal to one another. Thus, they are able to overlap without interfering. As a result, OFDM systems are able to maximize spectral efficiency without causing adjacent channel interference the frequency domain of an OFDM system is represented in the next figure (2-3) [3]



(a) (b)

Figure (2-3) OFDM channel (a) Multiple OFDM channel (b) single OFDM channel

OFDM communications systems are able to more effectively utilize the frequency spectrum through overlapping sub-carriers. These sub-carriers are able to partially overlap without interfering with adjacent sub-carriers because the maximum power of each sub-carrier corresponds directly with the minimum power of each adjacent channel. Below we illustrate the frequency domain of an OFDM system graphically. As you can see from the figure each sub-carrier is represented by a different peak. In addition the peak of each sub-carrier corresponds directly with the zero crossing of all channels [2]

2-3 MIMO System:

Generally multipath propagation would cause channel fading which is regarded as a harmful factor to wireless communication [3]. However, research shows that in a MIMO system, multipath transmission can be favorable to the wireless communication Multiple antennas (or array antennas) and multiple channels are used in the transmitter and receiver of MIMO system [3].

In the transmitter, the serial data symbol stream after the necessary space-time processing is sent to the transmit antennas, and then transmitted to the receiver In the receiver, the received data symbols are recovered through a variety of Space-time detection technologies In order to guarantee effective separation of the various sub-data symbol streams, the antennas must be separated with a sufficient distance (usually more than half a carrier wavelength) in order to prevent too much correlation between the received signals at the different antennas [3]. Figure (2-4) illustrates a MIMO system.

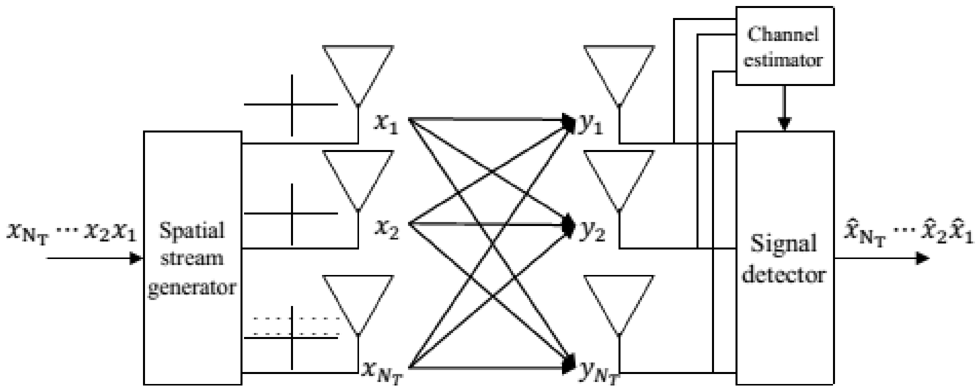


Figure (2-4) Block diagram MIMO system

As shown in Figure (2-4) signals are transmitted by antennas, and after propagating over the wireless channel such as the urban channel, they are received at the receive antennas. Each receiving antenna receives a superposition sum of the signals from the transmitting antennas.

2-4 Standards of MIMO- OFDM:

In 2004, a new task group (IEEE 802.11n) was formed to increase the wireless LAN data rate further. A very aggressive spectral efficiency higher than 15bps/Hz is proposed and it needs to offer interoperability with existing 802.11a/b/g networks. Wireless technologies including OFDM modulation and MIMO techniques with up to four antennas are adopted. Other measures put forward in the 802.11n proposals are higher code rate, low-density parity check code (LDPC), 20/40MHz channelization and reduction in guard interval overhead[6].

Originally the 802.16 and 16c defined a single-carrier system operating at frequencies ranging from 10 to 66 GHz. Later, the 802.16a defined several modes, such as single-carrier, OFDM and orthogonal frequency-division multiple access (OFDMA), in licensed and unlicensed bands from 2 to 11 GHz. The 802.16-2004, originally known as the 802.16d, includes the standards defined in the 802.16/16c and 16a. One year later, the 802.16e-2005 proposed a revision with more enhanced mobility than the 802.16d and it was thus called mobile WiMAX. The major revision is a scalable OFDM scheme in the OFDMA mode to restrict the Doppler Effect regardless of the bandwidth used. In addition, the highest carrier frequency was reduced from 11 to 6 GHz. The new standard also incorporated several MIMO techniques to enhance its performance in terms of coverage, frequency re-use and bandwidth efficiency Figure (2-5) show mobility transmission rate of several wireless communication system

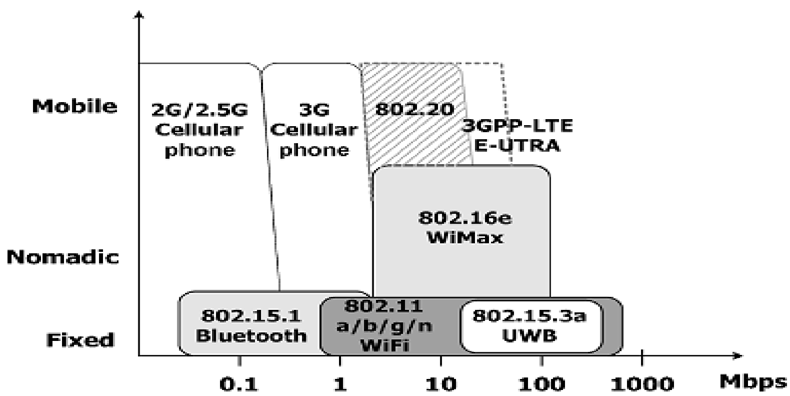


Figure (2-5) mobility transmission rate of several wireless communication system

2-5 General considerations:

OFDM is a technique for transmitting data in parallel by using a large number of modulated sub-carriers. These sub-carriers (or sub-channels) divide the available bandwidth and are sufficiently separated in frequency (frequency spacing) so that they are orthogonal. The orthogonality of the carriers means that each carrier has an integer number of cycles over a symbol period. Due to this, the spectrum of each carrier has a null at the center frequency of each of the other carriers in the system. This results in no interference between the carriers, although their spectra overlap. The separation between carriers is theoretically minimal so there would be a very compact spectral utilization [10].

OFDM systems are attractive for the way they handle ISI, which is usually introduced by frequency selective multipath fading in a wireless environment. Each sub-carrier is modulated at a very low symbol rate, making the symbols much longer than the channel impulse response. In this way, ISI is diminished. Moreover, if a guard interval between consecutive OFDM symbols is inserted, the effects of ISI can completely vanish. This guard interval must be longer than the multipath delay. Although each sub-carrier operates at a low data rate, a total high data rate can be achieved by using a large number of sub-carriers. ISI has very small or no effect on the OFDM systems hence an equalizer is not needed at the receiver side.

2-6 OFDM structure:

OFDM is a multi-carrier modulation In OFDM the channel is divided into a number of orthogonal sub-channels and the high speed data signal is converted into parallel low speed sub-streams those sub-streams are modulated on each sub-channel to be transmitted. Figure (2-6) illustrates the basic processing in an OFDM system

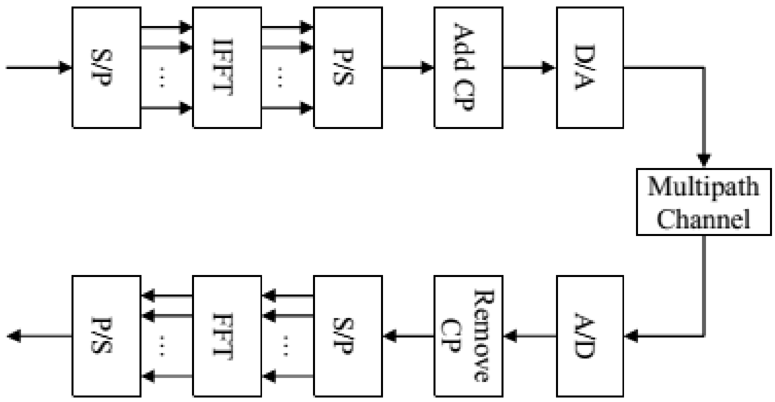


Figure (2-6) Block diagram traditional OFDM system

OFDM is effective against frequency selective fading and InterSymbol Interference (ISI) [3]. Since orthogonal sub-carriers are using as sub-channels, the spectral efficiency has been greatly improved Wireless data services are asymmetric, such that the transmission capacity requirement of downlink is greater than of uplink. While using OFDM the number of sub-channels can be adjusted flexibly to meet the different rate of downlink and uplink transmission [7].

OFDM can be jointly used with other access methods that improves the reliability of signal transmission in physical Generally, in OFDM, a certain length of the guard interval (GI) should be added and it overcomes the ISI when the duration of GI is greater than the maximum multipath delay spread of the radio channel. Typically the GI is filled with a cyclic prefix (CP) layer [6]. A major advantage of OFDM technology is that fast Fourier transform (FFT) inverse fast Fourier transform (IFFT) could be used for the implementation of modulation and demodulation of orthogonal sub-channels [6]. For the N point

FFT operation one needs N × log (N) complex multiplications, instead of N which would be required by a straight forward [8]

2-6-1 Mathematical description of OFDM

After description of the system, it is valuable to discuss the mathematical definition of the modulation system. This allows us to see how the signal is generated and how receiver must operate, and it gives us a tool to understand the effects of imperfections in the transmission channel. As noted above, OFDM transmits a large number of narrowband carriers, closely spaced in the frequency domain. In order to avoid a large number of modulators and filters at the transmitter and complementary filters and demodulators at the receiver, it is desirable to be able to use modern digital signal processing techniques, such as fast Fourier transform (FFT) mathematically each carrier can be described as a complex wave [12]

$$S_c(t) = A_c(t)e^{j|\omega_c t+\varphi_c t|} \qquad (2.1)$$

The real signal is the real part of $sc(t)$ Both $A_c(t)$ and $fc(t),$ the amplitude and phase of the carrier can vary on a symbol by symbol basis. The values of the parameters are constant over the symbol duration period t OFDM consists of many carriers. Thus the complex signals $s(t)$ is represented by:

$$\omega_n = \omega_\circ + n\Delta\omega$$

This is of course a continuous signal. If we consider the waveforms of each component of the signal over one symbol period, then the variables $A_c(t)$ and $fc(t)$ take on fixed values, which depend on the frequency of that particular carrier and so can be rewritten If the signal is sampled using a sampling frequency of 1/T, then the resulting signal is represented by

$$S_s(kT) = \frac{1}{N}\sum_{n=0}^{N-1} A_n\, e^{j|(\omega_o+n\Delta\omega)kT+\varphi_n|} \qquad (2.3)$$

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

$$t = NT$$

If we now simplify eqn. (2-3) without a loss of generality by letting $\mathrm{w} = 0$, then the signal becomes in general form of the inverse Fourier transform:

$$g(kT) = \frac{1}{N}\sum_{n=0}^{N-1} G(\frac{n}{NT})\, e^{j2\pi nk/N} \qquad (2.4)$$

In eq. (2-4), the function $A_n e^{j\phi_n}$ is no more than a definition of the signal in the sampled frequency domain, and $\mathrm{s(kT)}$ is the time domain representation. Eqns. 3 and 4 are equivalent if:

$$\Delta f = \frac{\Delta\omega}{2\pi} = \frac{1}{NT}$$

This is the same condition that was required for orthogonally Thus, one consequence of maintaining orthogonally is that the OFDM signal can be defined by using Fourier transform procedures the definition of the (N-point) discrete Fourier transform (DFT) is:

$$X_p[k] = \sum_{n=0}^{N-1} x_p[n] e^{-j(2\pi kn/N)} \qquad (2.5)$$

And the (N-point) inverse discrete Fourier transforms (IDFT):

$$x_p[n] = \frac{1}{N}\sum_{k=0}^{N-1} X_p[k] e^{j(2\pi kn/N)} \qquad (3.6)$$

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

Consider a data sequence (d_0, d_1, d_2, …, d_{N-1}), where each d_n is a complex number $dn = an + jbn$. ($an, bn = \pm 1$ For QPSK, $an, bn = \pm 1, \pm 3$ for 16QAM …)

$$D_k = \sum_{n=0}^{N-1} d_n e^{-j(2\pi nk/N)} \quad (2.7)$$

$$k = 0,1,2,\dots,N-1 \;\; fn = \frac{n}{ND\,T} \;\; ,tk = kD$$

Where T and D t is arbitrarily chosen symbol duration of the serial data sequence dn. The real part of the vector D has components
If these components are applied to a low-pass filter at time intervalsDt, a signal is obtained that closely approximates the frequency division multiplexed signal

$$y(t) = \sum_{n=0}^{N-1} a_n \cos(2\pi f_n t_k) + b_n \sin(2\pi f_n t_k) \quad (2.8)$$

$$0 \le t \le N\Delta t$$

The basic principle of OFDM is to split a high-rate data stream into a number of lower rate stream and transmitted them over a number of subcarriers as show in Figure (2-7). An OFDM signal is the combination of subcarriers that individual modulated by using phase shift keying (PSK) or quadrature amplitude modulation (QAM) techniques. The symbol of OFDM can be written as [12]

$$s(t) = Re\left\{\sum_{i=\frac{N_S}{2}}^{\frac{N_S}{2}-1} d_{\frac{i+Ns}{2}} \exp\left(j2\pi\left(f_c - \frac{i+0.5}{T}\right)(t-t_s)\right)^2\right\}, t_{s \le t \le t_s+T} \quad (2.9)$$

Where N_s the number of subcarriers, T is is the symbol duration and fc is the carrier frequency. The equivalent complex baseband notation is:

$$s(t) = Re\left\{\sum_{i=\frac{N_S}{2}}^{\frac{N_S}{2}-1} d_{\frac{i+Ns}{2}} \exp\left(j2\pi\frac{i}{T}(t-t_s)\right)^2\right\}, t_{s \le t \le t_s+T} \quad (2.10)$$

After the QAM, the original data will be modulated into I (inphase) and Q (quadrature) signal which correspond to real and imaginary parts in the equation.

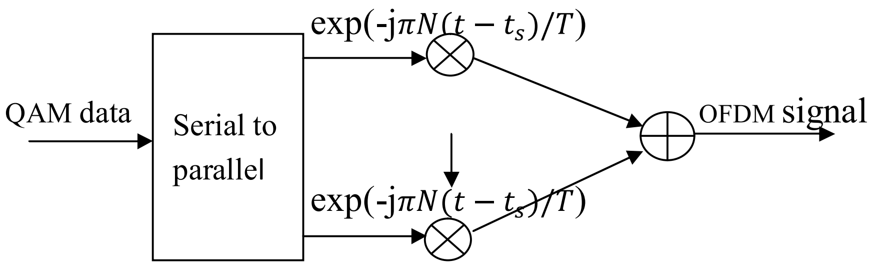


Figure (2-7) OFDM Modulator

The main concept in OFDM is the orthogonal of subcarriers. Each carrier is represented as sine or cosine wave, the area under one period of each wave is zero. Orthogonal allow simultaneous transmission on a lot of subcarriers in a short frequency without interference with each other's OFDM uses Discrete Fourier Transform (DFT) to map the input to a set of orthogonal basis function as show in Figure (2-8). In particle, it is more efficient to use to Fast Fourier Transform (FFT) to implement DFT. According to IEEE802.11n standards, the inverse Fast Fourier Transform (IFFT) is used in the transmitter and FFT is used in the receiver. IFFT significant reduces the amount of calculation rather than the IDFT (inverse DFT). The formulas for FFT and IFFT are [13]

$$x(k) = \sum_{n=0}^{N-1} x(n) \sin\left(\frac{2\pi kn}{N}\right) + j \sum_{n=0}^{N-1} x(n) \cos\left(\frac{2\pi kn}{N}\right) \qquad (2.11)$$

$$x(n) = \sum_{n=0}^{N-1} x(k) \sin\left(\frac{2\pi kn}{N}\right) - j \sum_{n=0}^{N-1} x(k) \cos\left(\frac{2\pi kn}{N}\right) \qquad (2.12)$$

Using IFFT and FFT in sequence will give back the original data as showing in figure (2-8).

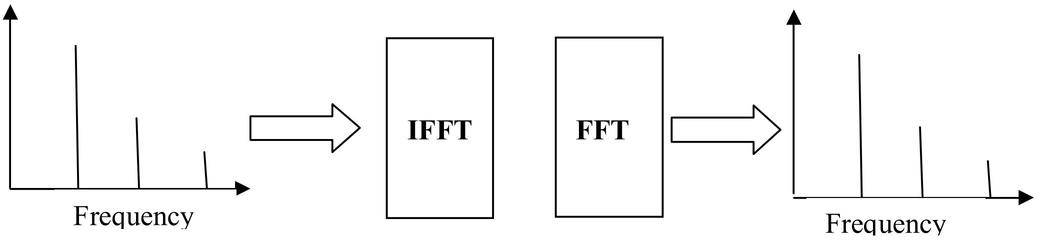


Figure (2-8) Block diagram IFFT/FFT processing

OFDM signals offers advantage that reduce the fading effect during the transmitting process. In the path from the transmitter to the receiver, there are reflections and obstructions that have negative effect on the signals or the fading effect. The original signal can reach the target in difference routes which can result delay and gain in the receiving side

With OFDM signal is divided into smaller subcarrier during the transmitting, OFDM signal can avoid that all of the subcarrier being damaged by fading effect. Therefore, instead of the whole signal being smashed up, we will lose just a small subset of bits at the receiving end, with a proper error-correcting code; we can easily recover the whole original signal. Orthogonal frequency-division multiplexing (OFDM) has developed into a popular scheme for broadband wireless communications. Modern wireless communication systems, such as WLAN digital TV systems and cellular communication systems, all adopt OFDM as one of the primary technologies. While OFDM systems are robust against multipath fading and have the ability to cope with severe interference and noise they are not ideal for environments where adversaries try to intentionally jam communications [14]

2-7 Basics of MIMO wireless communications

2-7-1 MIMO channel capacity:

Let us consider a point-to-point link where the transmitter has Mt antenna and the receiver has Mr antenna. We assume that the channel for the j^{th} transmit antenna to the i^{th} receiver antenna experiences frequency flat fading with complex channel gain h_{ij}, usually modeled as zero-mean unit-variance complex Gaussian random variables. As such, the received signal on the i^{th} receive antenna is given by:

$$y_i = h_{i1}x1 + h_{i2}x2 + \cdots + h_{iM_t}x_{M_t} + n_i \qquad (2.13)$$

Where x_{M_t} is the transmitted symbol from the j^{th} transmit antenna and n_i is the independent Gaussian noise with zero mean and variance $\sigma 2 \ = N0/2$. The discrete time MIMO channel model can be rewritten in matrix form as:

$$\begin{bmatrix} y_1 \\ y_1 \\ \vdots \\ y_{1M_t} \end{bmatrix} = \begin{bmatrix} h11 & h12 \ldots & h1M_t \\ h21 & h22 \ldots & h2M_t \\ \vdots & \vdots & hM_tM_t \\ hM_r1 & hM_r2 \ldots & hM_tM_t \end{bmatrix} \begin{bmatrix} x1 \\ x2 \\ \vdots \\ xM_t \end{bmatrix} + \begin{bmatrix} n1 \\ n2 \\ \vdots \\ nM_r \end{bmatrix} \qquad (2.14)$$

Or in matrix notation

$$y = Hx + n$$

High capacity and variable bit rate information transmission with high bandwidth efficiency are just some of the requirements that the modern transceivers have to meet in order for a variety of new high quality services to be delivered to the customers. Because in the wireless environment signals are usually impaired by fading and multipath delay spread phenomenon, traditional single carrier mobile communication systems do not perform well. In such channels, extreme fading of the signal amplitude occurs and Inter Symbol Interference (ISI) due to the frequency selectivity of the channel appears at the receiver side [14].

This leads to a high probability of errors and the system's overall performance becomes very poor. Techniques like channel coding and adaptive equalization have been widely used as a solution to these problems. However, due to the inherent delay in the coding and equalization process and high cost of the hardware, it is quite difficult to use these techniques in systems operating at high bit rates, for example up to several M bps. An alternative solution is to use a multi carrier system.

2-7-2 Significance:

With the rapidly growing technology, the demands for high speed data transmission are also increasing. OFDM is a multicarrier modulation technique which has the capability to fulfill this demand for large capacity. OFDM is reliable and economical to handle the processing power of digital signal processors. OFDM is used in many applications such as IEEE 802.11 wireless standard, Cellular radios, GSTN (General Switched Telephone Network), DAB (Digital Audio Broadcasting), DVB-T (Terrestrial Digital Video

Broadcasting) [3], HDTV broadcasting, DSL [4] and ADSL modems and HIPERLAN type II (High Performance Local Area Network)[10]

2-7-3 Orthogonality:

Orthogonality is the property when the signals are mutually independent of each other when the information signals are orthogonal, they can be transmitted simultaneously over the common channel without any interference. In case of loss of orthogonality, the performance of the communication system suffers degradation the general multiplexing schemes are essentially orthogonal. In Time Division Multiplexing multiple information signals are transmitted over the single channel but on unique time slots. Only one signal is transmitted during each slot to prevent any kind of interference among different information signals [9] .

Which makes the TDM system orthogonal in nature Similarly Frequency Division Multiplexing systems are orthogonal in frequency domain. In OFDM signal, all the subcarriers are well spaced out in frequency to maintain orthogonality among them Orthogonality is achieved by allocating a different subcarrier to each information signal. All the subcarriers are made orthogonal to each other as the baseband frequency of each sub carrier is chosen in such a way that it is an integral multiple of inverse of the symbol period Orthogonal Frequency Division Multiplexing (OFDM) is a kind of multi-carrier modulation, which divides the available spectrum into a number of parallel subcarriers and each subcarrier is then modulated by a low rate data stream at different carrier frequency which is given in [9]

The key to OFDM is maintaining orthogonality of the carriers. If the integral of the product of two signals is zero over a time period, then these two signals are said to be orthogonal to each other. Two sinusoids with frequencies that are integer multiples of a common frequency can satisfy this criterion. Therefore, orthogonality is defined by:

$$\int_{0}^{T} \cos\left(2\pi f_n(t)\right) \times \cos\left(2\pi f_m(t)\right) dt = \delta(n-m) \qquad (2.15)$$

Where (n-m) is the Dirac Delta function the subcarrier frequency f_n is defined as given in equation:

$$f_n = n\Delta f \qquad or \qquad \Delta f = \frac{f_s}{N} = \frac{1}{NT}$$

Here fs is the entire bandwidth and N is the number of subcarriers These subcarriers become orthogonal to each other when two different subcarrier waveforms are multiplied and integrated over symbol period results into zero

Where n and m are two unequal integers f_m is the fundamental frequency T is the period over which the integration is taken. For OFDM, T is one symbol period and f_m set to 1/T for optimal effectiveness

2-7-4 Protection against ISI

Intersymbol interference is a very common problem found in the existing high speed communication systems. It occurs when the transmitted data interferes with itself and is not Decoded correctly at the receiver The transmitted signal gets reflected from many large objects hence more than one copy of the signal reaches the receiver which is known as multipath. These copies of signal reach at the receiver after some delay and interfere with the original signal resulting into ISI [7]. Intersymbol interference can be classified into two types: interchannel ISI and intrachannel ISI. The non-ideal sub band filters leaks the signals from one channel to the adjacent channels which results into interchannel ISI, while intrachannel ISI results from channel dispersion Interchannel ISI is also known as adjacent channel interference or crosstalk. These two are defined as follows [8]

A. Intrachannel ISI

It is very easy to mathematically model intrachannel ISI. Consider a channel of length L

$$y_n = \sum_{k=0}^{L-1} h_k x_{n-k} = h_o x_n + \underbrace{\sum_{k=1}^{L-1} h_k x_{n-k}}_{\text{ISI term}} \qquad (2.16)$$

If the channel length is known, ISI can simply be eliminated by upsampling the signal by L before it is passed through the channel and on the receiver side, it is downsampled by L before modulation. But in this case, it is difficult to estimate the length of channel. Moreover, upsampling leads to high bit rate which increases transmission bandwidth requirements. Therefore, this technique is useful only for very short channels in which equalization is easier to implement. Thus, equalization comes out to be the only solution for removing intrachannel interference [9]

B. Interchannel IS1

Interchannel interference or the adjacent channel interference results from the non -ideal sub band filters. Thus, it can be reduced significantly by the use of filters having high spectral containment or simply high stop band attenuation. For this purpose, the long sub band filters are used which cause longer processing delays. Due to the presence of non-ideal sub band filters, ever y sub channel obtains a random unrelated contribution involving variable amplitudes from all other sub bands. AWGN model is used to approximate these contributions. If the channel is ideal, interchannel ISI does not have any effect due to orthogonality [9].

OFDM is very robust against ISI which makes it suitable for the high speed communication systems. When the data transfer speed is increased in the communication systems, the time

Duration for every single transmission gets shorter. But the delay time caused by multipath makes ISI a limitation in high data rate transmission. OFDM is the solution to this problem as it sends many low speed transmissions simultaneously adding a guard interval eliminates the effect of ISI but the guard period must be longer than the delay spread of channel. The remaining effects including amplitude scaling and phase rotation, resulting from ISI are Corrected by the channel equalization.

2-8 Principles of OFDM:

The main features of a practical OFDM system are as follows:

Some processing is done on the source data, such as coding for correcting errors,

- Interleaving and mapping of bits onto symbols. An example of mapping used is QAM
- The symbols are modulated onto orthogonal sub-carriers. This is done by using IFF or IDWT

- Orthogonality is maintained during channel transmission. This is achieved by adding a cyclic prefix to the OFDM frame to be sent. The cyclic prefix consists of the L last samples of the frame, which are copied and placed in the beginning of the frame. It must be longer than the channel impulse response.
- Synchronization: the introduced cyclic prefix can be used to detect the start of each frame. This is done by using the fact that the L first and last samples are the same and therefore correlated. This works under the assumption that one OFDM frame can be considered to be stationary.
- Demodulation of the received signal by using FFT.
- Channel equalization: the channel can be estimated either by using a training sequence or sending known so-called pilot symbols at predefined sub-carriers.

2-9 Fourier vs. Wavelet Based OFDM

Fourier based Conventional OFDM system has been a popular choice for wireless transmission over a long time for its transmission performances. In Fourier analysis we break up a signal into a set of an infinite sum of Sines and Cosines to exploit the Orthogonality relationship between them. On the other hand, using wavelet transform the signal is first decomposed by a low-pass (LP) and a high-pass (HP) filter. Half of the frequency components have been filtered out at filter outputs and hence can be down-sampled. We get approximation and detail coefficients from and filters respectively .

Where the wavelet's half-band low pass filter and high pass filter impulse responses In wavelet decomposition the details as well as the approximations can be split into a second level details and approximations.

These two sets of coefficients are obtained by performing convolution between the input signals and wavelet filter coefficients.

2-9-1 Fourier-based OFDM:

The main reason that the OFDM technique has taken a long time to become a prominence has been practical. It has been difficult to generate such a signal, and even harder to receive and demodulate the signal. The hardware solution, which makes use of multiple modulators and demodulators, was somewhat impractical for use in the communication systems [15]

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

At the transmitter, the signal is defined in the frequency domain. It is a sampled digital signal, and it is defined such that the discrete Fourier spectrum exists only at discrete frequencies. Each OFDM carrier corresponds to one element of this discrete Fourier spectrum. The amplitudes and phases of the carriers depend on the data to be transmitted. The data transitions are synchronized at the carriers, and can be processed together, symbol by symbol Figure (2-9).

Subcarrier orthogonality is the important factor in generating the OFDM signal. First of all, according to the modulation scheme, the signal is generated and processed by constellation mapping. Secondly, different modulation techniques are used in order to transmit the data in each carrier. In this work BPSK, QPSK, 16-QAM and 64-QAM modulation types are used and according to these techniques, the required amplitude and phase of each carrier are calculated Figure (2-9) illustrates a block diagram of conventional FFT-OFDM system. The important parts of this diagram are IFFT and FFT blocks at the transmitter and receiver respectively which are responsible for converting the information to the discrete time domain at the transmitter and to the frequency domain at the receiver. First, a random stream of data is generated as the input symbols, with length equal to the number of bits per frame. This is processed according to the different modulation techniques to get the desired constellation mapping. Next, these modulated data are converted from a serial vector to parallel data streams according to the numbers of subcarriers and the numbers of bits per frame. Finally the pilot subcarriers are inserted at predefined locations in the parallel data streams, and are then used to estimate and equalize the channel performance. The length of the parallel streams will then become equal to the size of the FFT (which is equal to the number of subcarriers and pilot subcarriers [14]

Generator used generates a bit stream. It is processed using QPSK or M-array QAM modulator to map the input data into symbols. These symbols are now sent through IFFT block to perform IFFT operation to generate N parallel data streams. Its output in discrete time domain is given by [14],

$$X_{k(n)} = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} X_m(i) e^{(j2\pi i/N)} \qquad (2.17)$$

To generate a baseband OFDM symbol, a serial digitized data stream is first channel coded and then modulated using phase shift keying (PSK) or quadrature amplitude modulation (QAM). These data symbols are converted from serial-to-parallel into N data constellation points before modulating the subcarriers using IFFT where Nis the number of IFFT points. The time domain OFDM modulated symbol output of the IFFT is converted back to a serial stream and a guard interval in the form of cyclic prefix is added to each OFDM symbol. The basic pulse shape for the symbols is rectangular which have large bandwidth due to its sinc shaped spectrum. Thus windowing is necessary to reduce the out of band energy of the side lobes. Then the symbol stream is converted to analog form for pass-band processing and transmission the receiver performs the exact opposite of the transmitter. After pass-band processing at the RF front-end the baseband processing will be performed.

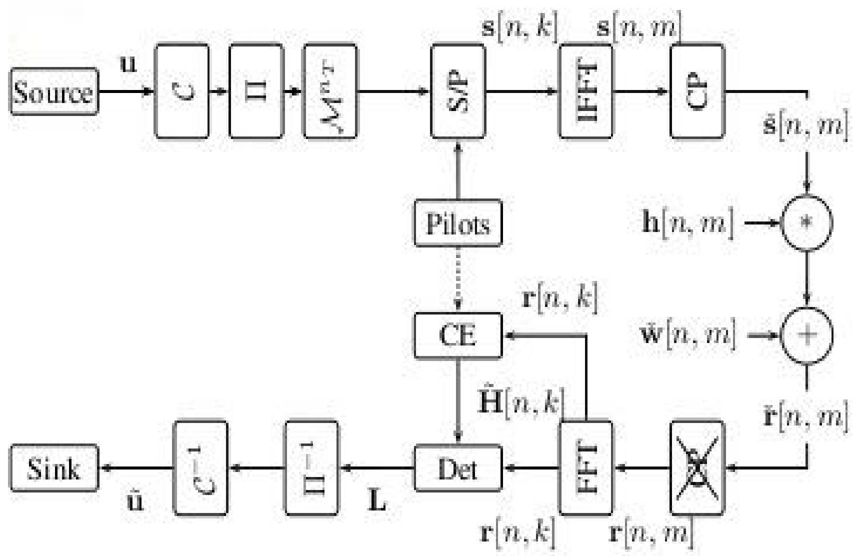


Figure (2-9) Block diagram of an OFDM-MIMO system using FFT

The transformed output is now appended with cyclic prefix. The cyclic prefix (CP) is added before transmission to mitigate ISI effect. It is usually 25% of the last part of the original OFDM symbol and this data is passed through AWGN channel with proper input power set. At the receiver, the reverse operation is done to obtain the original data back. The CP is removed and processed in the FFT block and finally passed through demodulator for data recovery the output of the FFT in frequency domain.

Mitigation of Interference ISI and ICI, ISI (Inter symbol interference) and ICI (Inter Carrier Interference) are influenced by shape of the basic pulse. Time dispersion contributes interference due to multipath effect and frequency dispersion due to non-linear effects of radio channel. In wireless scenario the channel effects cannot be controlled. But the pulse shape can be carefully designed to have minimum distortion for a given delay spread.

The wavelet transform allows more flexibility in the design of the pulse shape. Many researchers have proven that the wavelet based multi-carrier schemes are superior in suppressing ICI and ISI as compared to the traditional Fourier based systems [14].

2-9-2 discrete wavelet-based OFDM:

Similar to the conventional OFDM and Discrete wavelet transform (DWT) systems a functional block diagram of OFDM based on DWT is shown in figure (2-10). At the transmitter an inverse (IDWT) block is used in place of inverse FFT (IFFT) block in conventional OFDM system. At the receiver side a DWT is used in place of FFT block in conventional OFDM system.

There are various advantages of using wavelets for wireless communication systems. First, subcarriers of different bandwidth and symbol length can be created. Furthermore, they satisfy perfect reconstruction and orthonormal base properties by employing the reconstruction filters (LPF and HPF) as a conjugate quadrature filters or quadrature mirror filters (QMFs) [2]

This section discusses the alternative way to implement OFDM using DWT. In Wavelet based OFDM (DWTOFDM), the time-windowed complex exponentials are replaced by wavelet “carriers", at different scales (j) and positions on the time axis (k).These functions are generated by the translation and dilation of a unique function, called "wavelets mother" and denoted by

$$\psi_{j,K}(t) = 2^{-\frac{j}{2}}\psi\left(2^{-j}(t-k)\right) \qquad (2.18)$$

Her orthogonality of these carriers relies on time location (k) and scale index (j). Wavelet carriers exhibit better time-frequency localization than complex exponentials while DWT-OFDM implementation complexity is comparable to that of FFT- OFDM. The key point ‘orthogonality’ is achieved by generating members of a wavelet family according to Equation (2-19)

$$\langle \psi_{j,k}(t), \psi_{m,n}(t) = \{| \begin{matrix} 1, j = m\ k = n \\ 0, otherwise \end{matrix} \rangle \qquad (2.19)$$

Similarly as for the FFT-OFDM system, apply the DWT on the received signal to obtain the signal in the discrete wavelet domain:

$$Z_m = \mathrm{DWT}(\mathrm{Z_k}) \qquad (2.20)$$

$$= \mathrm{DWT}(\mathrm{X_k} + \mathrm{N_k})$$

$$= \mathrm{DWT}\{\mathrm{X_k}\} + \mathrm{DWT}\{\mathrm{N_k}\}$$

$$Z_m = X_k^w + N_k^w$$

Where$X$ andNwk represent the DWT of the signals Xk and Nk respectively, Where w is called the scaling filter Reconstruction algorithm of the DWT-OFDM system the important part in the transmitter of the DWT-OFDM scheme is the Inverse Discrete Wavelet Transform (IDWT) which is called the reconstruction algorithm [2] Data to be transmitted are typically in the form of a serial data stream, PSK or QAM modulations can be implemented in the proposed system the choice depends on various factors like the bit rate and sensitivity to errors. The transmitter accepts modulated data (in this project we use 16 and64QAM). This stream is passed through a serial to parallel (S/P) converter, giving N lower bit rate data stream and then this stream is modulated through an IDWT matrix realized by an N-band synthesis Before the receiver can demodulate the subcarriers, it has to perform the synchronization. For the proposed system, known data interleaved among unknown data are used for channel estimation. Then, the signal is down sampled by N and demodulated using elements of the DWT matrix realized by an N-band analysis

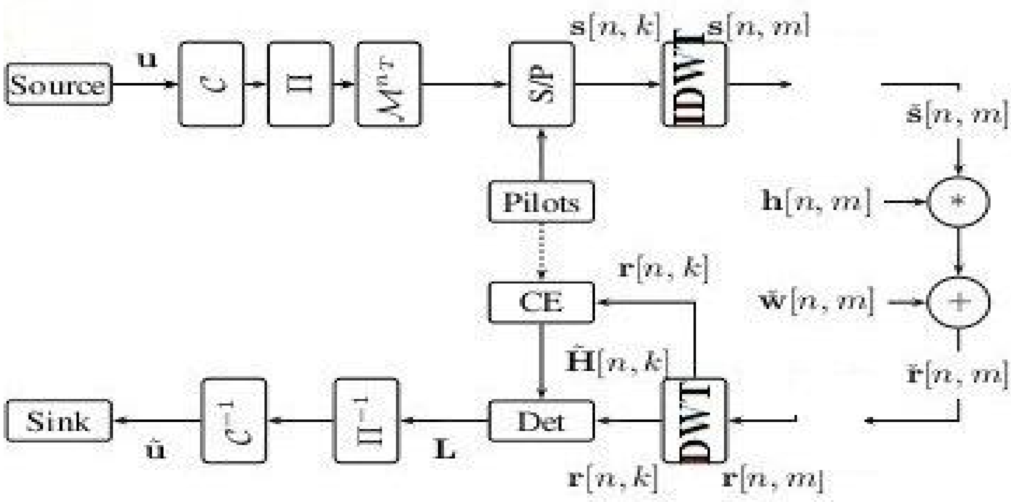


Figure (2-10) Block diagram of an OFDM-MIMO system using DWT

2-10 Advantages of OFDM:

1. OFDM allows simultaneous transmission of subcarriers over a common channel thus making the efficient use of the available spectrum.

2. OFDM divides the frequency channel into many narrowband flat fading sub-channels which makes it more resistant to frequency selective fading.

3. OFDM makes use of cyclic prefix which helps in eliminating ISI and ICI.

4. If the symbols are lost due to frequency selectivity of channel, they can be recovered using appropriate channel coding and interleaving.

5. Channel equalization is potentially simpler as compared to the adaptive equalization techniques used in single carrier systems.

6. Maximum likelihood decoding can also be used in OFDM with less complexity.

7. OFDM is comparatively less sensitive to the timing offsets than single carrier Systems.

8. FFT and IFFT are used in OFDM for modulation and demodulation in place of arrays of sinusoidal generators which makes it computationally efficient and cost effective.

9. It provides better protection against co -channel interference as well as impulsive parasitic noise.

10. OFDM randomizes the burst errors effectively which are caused due to fading and allows proper reconstruction even without forward error correction

2-11 Disadvantages of OFDM:

1. The amplitude of OFDM signal has a very large dynamic range. Therefore, RF power amplifiers are required which possess high peak to average power ratio (PAPR).

2. OFDM systems are more sensitive to the carrier frequency offset and drift as compared to the single carrier systems Most research centers throughout the world are mainly focusing their work on these two topics in their attempt to optimize OFDM

2-12 PAPR Reduction Techniques

2-12-1 PAPR Definition

PAPR is defined as the ratio of the maximum peak power to that of average power of the complex passband signal.

Theoretically, large peaks in OFDM system can be expressed as Peak-to-Average Power Ratio or referred to as PAPR, in some literatures, also written as PAR. It is usually defined as [4]

$$PAPR = \frac{P_{peak}}{P_{average}} = 10log_{10}\frac{\max\,[|x_n|^2]}{\mathrm{E}[|\mathrm{x_n}|^2]} \qquad (2.22)$$

Where P peak represents peak output power P average means average output power $E[|x_n|]$ denotes the expected value xn represents the transmitted OFDM signals which are obtained by taking IFFT operation on modulated input symbols X_k Mathematical **Xn** is expressed as:

$$x_n = \frac{1}{\sqrt{N}}\sum_{k=0}^{N-1} X_x W_N^{nk} \qquad (2.23)$$

For an OFDM system with N sub-carriers, the peak power of received signals is N times the average power when phase values are the same. The PAPR of baseband signal will reach its theoretical maximum PAPR(dB)=10log(N) For example for a 16 sub-carriers system the maximum PAPR is 12 dB. Nevertheless, this is only a theoretical hypothesis. In reality the probability of reaching this maximum is very low By observing the simulation result in can make a conclusion that the amplitude of OFDM signal reaches its peak value when the input data sequence has a larger consistency.

At the same time, the maximum PAPR value will be reached as well.

Another commonly used parameter is the Crest Factor (CF), which is defined as the ratio between maximum amplitude of OFDM signal s(t) and root-mean-square (RMS) of the waveform. The CF is defined as:

$$CF\big(s(t)\big) = \frac{\max\,[|s(t)|]}{\mathrm{E}[||\mathrm{s(t)}|^2|]} = \sqrt{\mathrm{PAPR}} \qquad (2.24)$$

In most cases, the peak value of signal x(t) is equals to maximum value of its envelope |x(t)| However it can be seen from Fig. 2.11 that the appearance of peak amplitude is very rare, thus it does not make sense to use max |x(t)| to represent peak value in real Application. Therefore, PAPR performance of OFDM signals is commonly measured by certain characterization constants which are related to probability

There are many different algorithms that have been proposed to solve the high PAPR problem of OFDM system. These reduction solutions can be roughly divided into three categories [5]:

a. Signal Distortion

One of the most pragmatic and easiest approaches is clipping and filtering which can snip the signal at the transmitter so as to eliminate the appearance of high peaks above a certain level. Clipping can be implemented to the discrete samples prior to digital-to-analog convertor (DAC) or by designing analog-to-digital-convertor (DAC) and/or amplifier with saturation levels which are lower than the dynamic range [17] But due to the nonlinear

distortion introduced by this process orthogonality will be destroyed to some extent which results in serious in band noise and out of band noise. In-band noise cannot be removed by filtering, it decreases the bit error rate (BER). Out-of band noise reduces the bandwidth efficiency but frequency domain filtering can be employed to minimize the out-of-band power. Although filtering has a good effect on noise suppression, it may cause peak re-growth. To overcome this drawback, the whole process is repeated several times until a desired situation is achieved. Furthermore some other novel proposals which combine this method with coding and/or signal scrambling have already been studied by other researcher [18].

b. Signal Scrambling Techniques

The fundamental principle of this technique is to scramble each OFDM signal with different scrambling sequences and select one which has the smallest PAPR value for transmission. Apparently, this technique does not guarantee reduction of PAPR value below to a certain threshold, but it can reduce the appearance probability of high PAPR to a great extent this type of approach include: Selective Mapping (SLM) and Partial Transmit Sequences (PTS). SLM method applies scrambling rotation to all sub-carriers independently while PTS method only takes scrambling to part of the sub-carriers. These two methods can be applied to any scenarios without restriction on the number of sub-carriers and type of modulation. However, for successful recovery of the signal at the receiver , additional information is needed that leads to low bandwidth utilization and high hardware complexity for implementation [15].

c. Coding Techniques

The core of encoding method is to apply special forward error correction technique to remove the OFDM signals with high PAPR. The classical schemes include linear block code , Golay codes and Reed-Muller code . As far as linear block code method is concerned, it is only suitable to the scenario which has a small number of sub-carriers, which results in limited applications. Reed-Muller code is a high efficiency coding scheme, it obtains a lower PAPR for the second order cosets code by classifying the Walsh-Hadamard transform (WHT) spectrum of the code words. By using Reed-Muller code, PAPR can be reduced to 3dB at most with a good error correcting performance. However, all in all, the encoding method is limited to types of constellation.

2-12-2 Impact of PAPR on MIMO OFDM performance

The peak to average power ratio (PAPR) of a transmitted signal is one of main challenges in wideband multi-carrier systems that use orthogonal frequency division multiplexing (OFDM) or multiple-input multiple-output (MIMO) OFDM. Understanding the effects of PAPR on OFDM and MIMO-OFDM systems is critical when determining what techniques to use improve system performance. For the purposes of this thesis, use the terms OFDM and

MIMO-OFDM interchangeably without affecting the meaning of PAPR The use of a large number of subcarriers introduces a high PAPR in OFDM systems. PAPR can be defined as the relationship between the maximum power of a sample in a transmit OFDM symbol and its average power [15]

$$PAPR = 10log_{10}\frac{P_{peak}}{P_{average}}(\text{dB}) \qquad (2.25)$$

Where P_{peak} and $P_{average}$ is power of given OFDM system the same definition of PAPR is applied to MIMO-OFDM systems. A high PAPR appears when a number of subcarriers of a given OFDM symbol are out of phase with each other. PAPR can vary up to its theoretically maximum of $10\log_{10}$ (N) (dB) where N is the number of subcarriers.

2-12-3 Probability Distribution Function of PAPR

According to central limit theorem, for a large number of sub-carriers in multi-carrier signal the real and imaginary part of sample values in time-domain will obey Gaussian distribution With mean value of 0 and variance of 0.5 Therefore, the amplitude of multi-carrier signals Follows Rayleigh distribution with zero mean and a variance of N times the variance of one Complex sinusoid [15] its power value obeys an X distribution with zero mean and 2 degrees of freedom Cumulative Distribution Function (CDF) is expressed as follows:

$$F(z) = (1 - \exp(-z)) \qquad (2.26\ )$$

Equation (2-25) can be written as In this situation, PAPR can be written as Since PAPR can have random variable value, it can be denoted as complementary cumulative distribution function (CCDF) When CCDF, PAPR0 threshold is exceed, PAPR value of OFDM sign can be expressed as:

$$CCDF\left(\mathrm{PAPR}\left(\mathrm{x(n)}\right)\right) = \mathrm{P_r}\left(\mathrm{PAPR}\left(\mathrm{x(n)}\right)\right) > \mathrm{PAPR_0} \qquad (2.27)$$

Depending to the independent N data block, SISO OFDM in the sign PAPR CCDF can be

$$P = P_r\left(PAPR\left(x(n)\right) > PAPR_0\right) = 1 - (1 - e^{-PAPR_0})^N \qquad (2.28)$$

Denoted as the following If this equation is composed for MIMO-OFDM system PAPR value on the i.th transmitted

$$P_r(PAPR_{MIMO-OF\mathrm{DM}} > PAPR_0) = 1 - (1 - e^{-PAPR_0})^{M_t N} \qquad (2.29)$$

The chapter four show complementary Cumulative Distribution Function curve (CCDF) Using DWT and FFT for different number of sample N