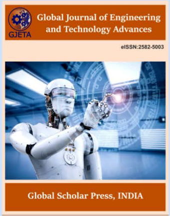
Global Journal of Engineering and Technology Advances

eISSN: 2582-5003
Cross Ref DOI: 10.30574/gjeta
Journal homepage: https://gjeta.com/



(Research Article)

An overview of orthogonal frequency division multiplexing principles, architecture, and its application

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Global Journal of Engineering and Technology Advances, 2022, 12(01), 120–130

Publication history: Received on 16 June 2022; revised on 20 July 2022; accepted on 22 July 2022

Article DOI: https://doi.org/10.30574/gjeta.2022.12.1.0118

Abstract

In this work, Orthogonal Frequency Division Multiplexing's (OFDM) principles, implementation design or high-level system architecture and application were reviewed. The condition for orthogonality, frequency spacing between consecutive subcarriers (called frequency spacing) was established analytically with practical instance highlighted. The review also covers Fast Fourier Transform (FFT) which serves as a bank of demodulators while Inverse Fast Fourier Transform (IFFT) serves as a bank of modulators in an OFDM system, advancement in OFDM, Quadrature modulation types (Binary Phase Shift Keying, 4-Quadrature Amplitude Modulation, 8-Quadrature Amplitude Modulation, 16-Quadrature Amplitude Modulation, and 64-Quadrature Amplitude Modulation QAM) and spectrum efficiency was also covered. Several technologies that use OFDM were mentioned but attention was given to its usage in Wireless LAN 802.11a.

Keywords: Orthogonal Frequency Division Multiplexing; OFDM; WLAN; Fast Fourier Transform; 4G

1. Introduction

With Wideband Code Division Multiple Access, a tremendous high data rate was achieved and with advanced technologies, the demand for a higher data transmission rate is a continuous one. One of the drivers for this demand is the advances made in multimedia and social networks that warrant more and more transmission of video, audio, and graphical messages; OFDM provides means of meeting these demands.

More importantly, OFDM is a special case of FDM (Frequency Division Multiplexing) where there is no band-guard, and the bandwidth of adjacent carriers overlaps each other. OFDM uses multiple sub-carriers(sub-channels) that transmit a data stream at a lower rate; this is a case of multi-carrier transmission [1].

OFDM offered efficient spectrum utilization as the bandwidth of adjacent carriers overlap, but there is no inter-channel interference as subsequent carriers are separated by constant bandwidth which is the inverse of each information symbol duration (sometimes called sub-carrier spacing), and this is the orthogonality principle [2]. Figure 1 depicts the bandwidth overlap of sub-carriers in OFDM.

Inverse Fast Fourier (IFFT) and Fast Fourier Transform implementation on Digital Signal Processor has made OFDM modulation techniques feasible regarding practical realization on 3G, 4G and 5G devices today. IFFT and FFT play a significant role OFDM scheme [3][4].

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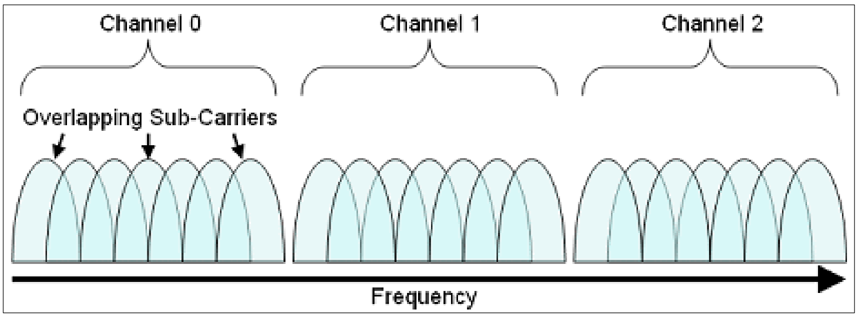

Figure 1 Bandwidth overlap of subcarriers in OFDM [1]

2. Basic Principles of OFDM

OFDM is achieved by using a combination of some basic principles such as frequency orthogonality, QAM, IFFT, and FFT. A quick review of these principles will be done before examining OFDM system architecture.

2.1. Frequency orthogonality

Signal frequencies that are orthogonal to each other have their bandwidth overlapped with no signal interference. Two signals g1(t) and g2(t) are said to be orthogonal if the integral of their product over a period is zero [5].

$$\int_{t1}^{t2} g1(t)g2(t) \quad dt = 0$$

where,

$$g1(t) = \cos(2\pi f1t + \theta) \text{ and } g2(t) = \cos(2\pi f2t)$$

If the symbol rate is 1/T symbols/s then the condition for orthogonality is further modified to what is shown below

$$\int_0^T cos(2\pi f1t + \theta)cos(2\pi tf2t) \quad dt = 0 \dots\dots\dots\dots \qquad (1)$$

Such that

$$cos\theta \int_0^T cos(2\pi f1t)cos(2\pi tf2t) \quad dt \text{ - } sin\theta \int_0^T sin(2\pi f1t)cos(2\pi tf2t) \quad dt{=}0 \quad \dots\dots\dots\dots \qquad (2)$$

From the above equation (2), since f1+f2>>1 then we have

$$cos\theta sin2\pi(f1 - f2)T + sin\theta[cos2\pi(f1 - f2)T - 1]{\approx}0 \quad \dots\dots\dots\dots \qquad (3)$$

The above equation can only be zero only if $sin2\pi(f1 - f2)T = 0$ and at the same time $cos2\pi(f1 - f2)T{=}1$ for an arbitrary value of θ.

Hence

$$2\pi(f1 - f2)T = 2n\pi \qquad \dots\dots\dots\dots \qquad (4)$$

$f1 - f2 = n/T$ in a standard form $f1 - f2 = \pm n/T$

here, n is an integer with a minimum value of n is 1

$$f1 - f2 = 1/T \qquad \dots\dots\dots\dots \qquad (5)$$

The minimum spacing between two signal frequencies f1 and f2 for orthogonality to be established is 1/T although multiples of 1/T(n/T) can still achieve the same result [3].

Figure 2 below is the frequency spectrum of the orthogonal sub-carriers, and it can be observed that the frequency spectrum of each sub-carrier has zero-crossing at the central frequency of adjacent sub-carriers [2] which results in spectral efficiency.

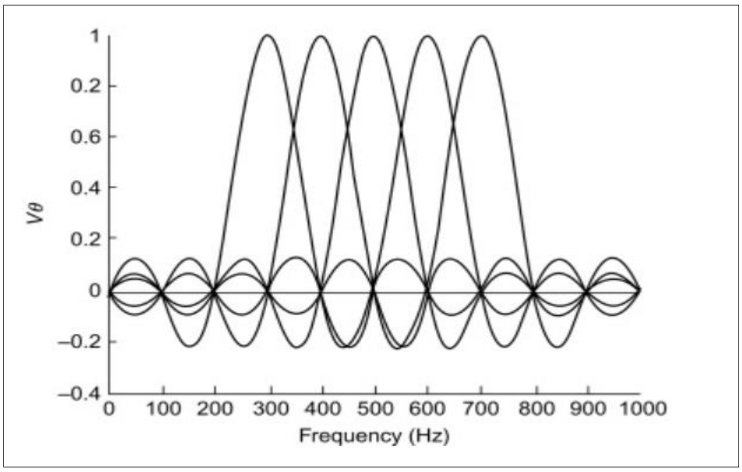

Figure 2 Overlapped Bandwidth of Orthogonal subcarriers [6]

In IEEE 802.11a Wireless LAN standard, the symbol duration T is 3.2µs, and this implies that spacing between subcarriers is:

$$\frac{\pm \mathrm{k}}{T} = \pm 312.5\mathrm{KHz}, \pm 625\mathrm{KHz}...$$

1.1 Fast Fourier Transform and Inverse Fourier Transform

Fourier Transform is concerned with the representation of continuous signal f(t) in the frequency domain as shown in equation (6). It maps time series to corresponding frequency series represented by amplitude and phase.

$$f(jw) = \int_{-\infty}^{\infty} f(t)e^{-jwt}dt \qquad \dots\dots\dots\dots \qquad (6)$$

In case of sampled continuous signal with N samples and time interval T, f(t) now becomes f [0], f[1], f[2],….,f[N-1] as shown in equation(7).Each sample is regarded as an impulse area.

$$f(jw) = \int_{-\infty}^{(N-1)T} f(t)e^{-jwt}dt$$

$$= f[0]e^{-j0} + f[1]e^{-jwT} + f[2]e^{-j2wT} + \dots + f[N-1]e^{-jw(N-1)T} \quad \dots\dots\dots\dots \quad (7)$$

$$\text{i.e.} \quad f(k) = \sum_{n=0}^{N-1} f[n]e^{-jwkT}$$

Where n=0,1,2, 3……N-1.

The expression above is referred to as Discrete Fourier transform (DFT). In practice, Fast Fourier Transform is used which is a much faster version of DFT as it utilizes a faster algorithm to do what DFT does in much less time.

In OFDM, FFT is the mechanism used in the multi-carrier (array of sub-carriers) demodulation. The reverse operation of FFT is called Inverse Fast Fourier Transform (IFFT) which is the transformation of a signal in the frequency domain to the time domain denoted by the expression below (equations (8) and (9))

$$f(t) = \int_{-\infty}^{(N-1)T} f(k)e^{jwt}dt \quad \dots\dots\dots \quad (8)$$

$$= f[0]e^{j0} + f[1]e^{jwT} + f[2]e^{2wT} + \dots\dots + f[N-1]e^{jw(N-1)T} \quad \dots\dots\dots \quad (9)$$

$$\text{i.e.} \quad f(n) = \sum_{k=0}^{N-1} f[k]e^{-jwkT}$$

Where k=0, 1,2, 3,..,N-1.

2.2. Modulation Types

Several quadrature modulation types can be adopted in the OFDM system, among them are BSPK, QPSK (4QAM), 8PSK (8QAM), 16QAM, 32QAM or 64-QAM. A symbol in BSPK, QSPK,8PSK,16QAM, 32QAM and 64QAM represent one, two, three, four, five and six bits respectively as shown in Table 1 below. Release 12 and 15 of the Third Generation Partnership Project (3GPP) standard discussed 256-QAM and 1024-QAM respectively [7]

Table 1 Modulation types and corresponding Bits per symbol

Modulation Type	Bits per symbol	Symbol Rate
BPSK	1	1 x bit rate
QPSK(4QAM)	2	1/2-bit rate
8PSK(8QAM)	3	1/3-bit rate
16QAM	4	1/4-bit rate
32QAM	5	1/5-bit rate
64QAM	6	1/6-bit rate

2.3. OFDM System Architecture

The OFDM system consists of two major parts, the transmitter, and the receiver. The transmitter comprises the encoder, serial-to-parallel converter, IFFT modulator, cyclic prefix insertion and Radio-frequency-Upconverter. The receiver part comprises of Radio-frequency- Downconverter, Serial-to-parallel converter, Cyclic prefix extraction demodulator, Parallel-to-Serial converter, and decoder [7].

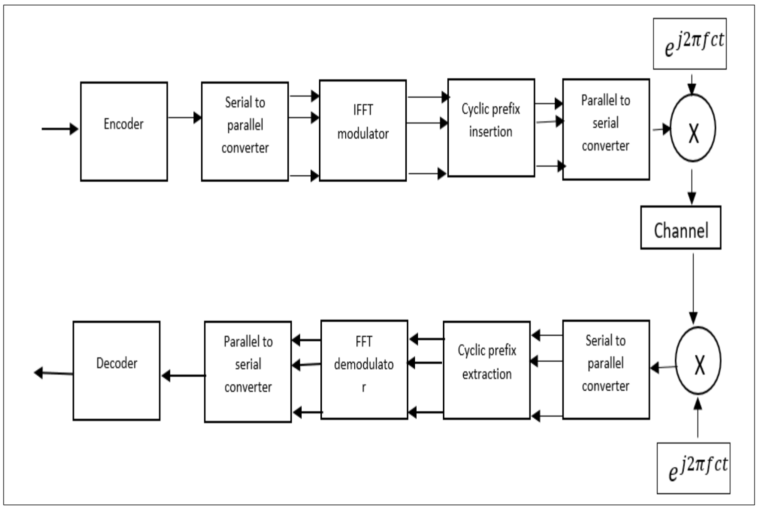

Figure 3 OFDM system architecture

The original message bits are passed into the encoder stage that adds extra bits to the original message bits for error detection or correction at the receiver end. There are various coding rates supported such as ½, 2/3,3/4 etc. In the case of ½ channel coding rate, for every one message bit, there is a corresponding parity bit for error detection.

$$Coding\ Rate = \frac{Number\ of\ Useful\ Bit}{Total\ Number\ of\ Bit} \quad \dots\dots\dots\dots \quad (10)$$

The bit stream from the encoder is then passed through the Serial-to-Parallel converter. The Serial-to-Parallel converter breaks the bit stream into parallel sub-streams. Each of the sub-streams can now be easily mapped to corresponding values in the constellation table or modulation scheme [6].

For 8bits stream fed into a Serial-to-Parallel converter will generate four 2bits parallel sub-streams (output) if 4QAM is to be used as depicted in figure 4.

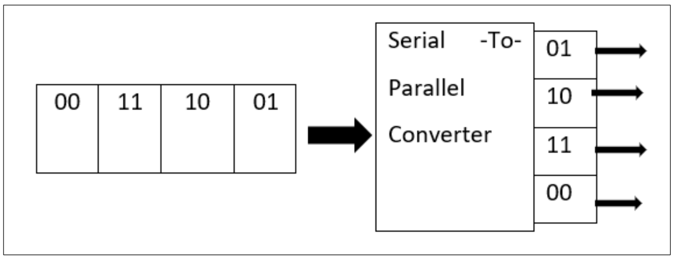

Figure 4 Serial-To-Parallel Converter for 8bit to 4 2bit parallel output

OFDM can support BSP, 4QAM, 16QAM, 64QAM and up to 4096.The higher order QAM modulation types are more susceptible to noise and interference though they provide much higher data throughput. Due to this, many radio communications systems now use dynamic adaptive modulation techniques. They sense the channel conditions, that's the link quality index and adapt the modulation scheme to obtain the highest data throughput for the given conditions. Below is the table of the radio link quality index and corresponding, modulation type and code rates specifically for Long Term Evolution (LTE).

Table 2 Combination of the radio link quality index and modulation schemes with corresponding coding schemes for LTE

CQI Index	Modulation	Code-rate
0	Out of range	
1	QPSK(4QAM)	0.076171875
2	QPSK(4QAM)	0.1171875
3	QPSK(4QAM)	0.188476563
4	QPSK(4QAM)	0.30078125
5	QPSK(4QAM)	0.438476563
6	QPSK(4QAM)	0.587890625
7	16QAM	0.369140625
8	16QAM	0.478515625
9	16QAM	0.6015625
10	64QAM	0.455078125
11	64QAM	0.553710938
12	64QAM	0.650390625
13	64QAM	0.75390625
14	64QAM	0.852539063
15	64QAM	0.92578125

In Table 2, the radio channel quality is represented by Channel Quality Index (CQI) which ranges from 1 to 15; alongside the CQI, there is also a corresponding modulation type and code rate.

The 64QAM modulation type is used when the CQI is from 10 to 15, and it provides the most efficient spectrum utilization as it uses a high code rate compared with 4QAM and 16QAM as shown in the graph of Figure 5 below. However, 64QM is more susceptible to noise and interference compared to 16QAM and 4QAM.

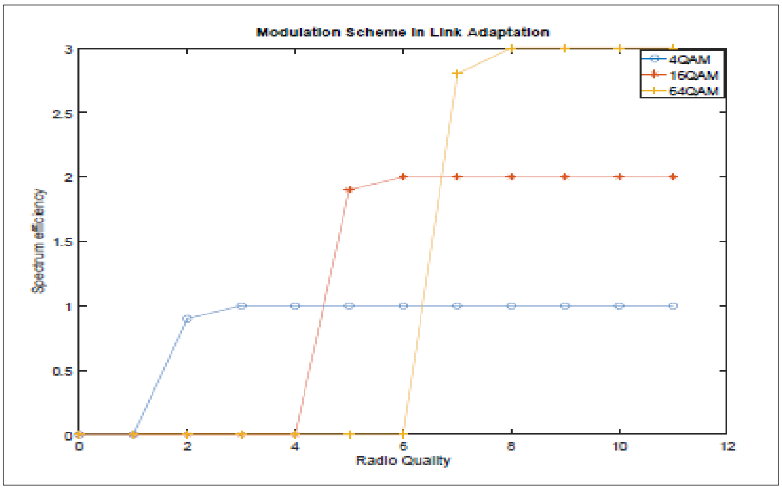

Figure 5 Modulation schemes and spectrum efficiency

The *N* parallel sub-streams which are the output of the Serial-to-Converter serve as *N* input to the IFFT sub-system. Each sub-stream is a signal symbol and can be considered a complex number within the IFFT system. Below is the constellation diagram of 4QAM.

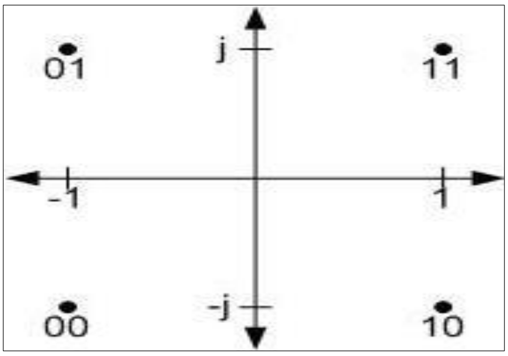

Figure 6 4QAM constellation

Each of the constellation points is a complex number $(a + jb)$ and can also be represented in terms of magnitude and phase [3].

Table 3 4-QAM bits and complex number representation

Binary Data	Complex form[f(k)]	Magnitude and Angle[f(k)]
11	1+j	√2/45∘ or √2(cos45∘+jsin45∘)
01	-1+j	√2/315∘ or √2 (cos315∘+jsin315∘)
00	-1-j	√2/225∘ or √2(cos225∘+jsin225∘)
10	1-j	√2/135∘ or √2 cos135∘+jsin135∘)

IFFT operation uses each signal symbol to modulate the corresponding sub-carrier (where we have N sub-carriers which are sinusoidal signals mapped to N sub-streams). If 4QAM is used, we will have four subcarriers phase modulated (the peak magnitudes of sub-streams are the same, in this case as extracted from table 3, it is √2. So irrespective of what symbol is transmitted, the peak amplitudes of the modulated sinusoids are the same).

$$S[k(t)] = e^{j2\pi fkt} \qquad \dots\dots\dots\dots \qquad (11)$$

Where k=1,2. …. (N-2), (N-1), N and $S[k(t)]$ are the sub-carrier signals and

$S[1(t)]$ is the first sub-carrier signal represented by

$S[1(t)] = e^{j2\pi ft}$ or cos $2\pi ft$,first subcarrier sinusoid ignoring the imaginary part.

$S[2(t)] = e^{j4\pi ft}$ or cos $4\pi ft$, second subcarrier sinusoid.

$S[(N-1)(t)] = e^{j2\pi f[N-1]t}$ *or cos* $2\pi f[N-1]t$, *N-1 subcarrier sinusoid.*

$S[N(t)] = e^{j2\pi fNt}$ *or cos* $2\pi fNt$ *,N subcarrier sinusoid.*

4QAM modulation of the first and last carrier by symbol $(1+j)$ and $(-1-j)$ respectively are demonstrated below mathematically

$$y(1)=2\underline{/45\circ}\ * \cos 2\pi ft \qquad \dots\dots\dots\dots \qquad (12)$$

$$=\sqrt{}2\cos(2\pi ft + \dots\dots\dots\dots$$

The phase shift of 45 ∘ .

Alternatively, the modulated first sub-carrier can be represented as:

$$y(1) = \sqrt{2}\, e^{j45} * e^{j2\pi ft}$$

$$= \sqrt{2} e^{j(2\pi ft+45*)} \qquad \dots\dots\dots\dots \qquad (14)$$

For the last sub-carrier:

$$y(n) = 2/225\circ * \cos 2\pi Nft \qquad \dots\dots\dots\dots \qquad (15)$$

$$y(n) = \sqrt{2}\cos(2\pi Nft + 225) \qquad \dots\dots\dots\dots \qquad (16)$$

The phase shift of 225 ∘ .

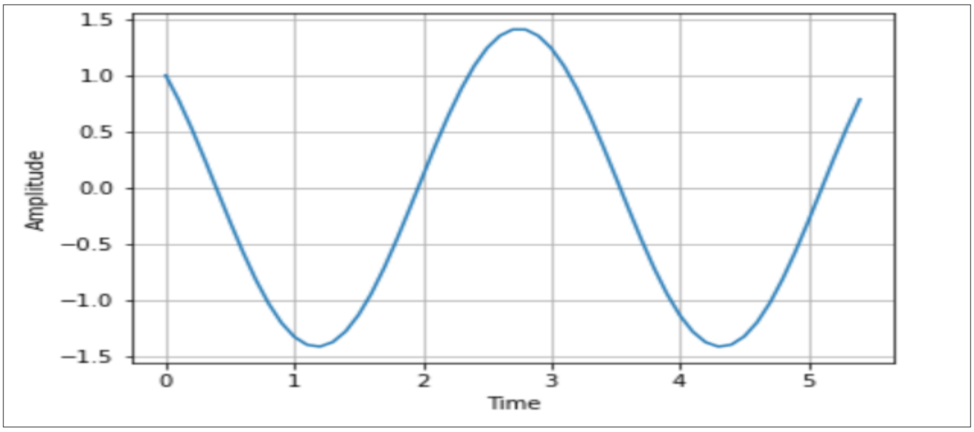

Figure 7 First sub-carrier with a phase shift of 45 ∘ after being modulated by √2/45 ∘

Figure 7 above shows the carrier signal shifted by 45o and the figure shows the application of the above principle in 4QAM. Figure 8 shows QAM output phase and amplitude against time relationship [8].

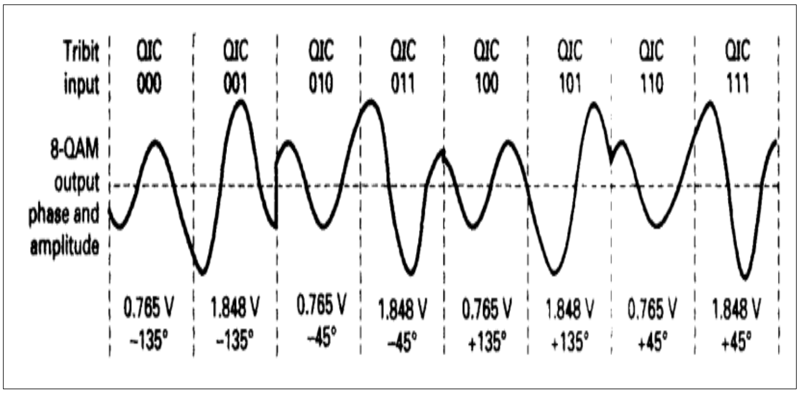

Figure 8 QAM output phase and amplitude versus time relationship [8]

In a situation where 8QAM, 16QAM, 32QAM or 64QAM is used, the sub-carrier signals are both phase and amplitude modulated. The outputs of the IFFT module are passed to the parallel input of the cyclic prefix insertion module. The cyclic prefix is inserted to prevent inter-symbol and inter-block interference caused by multi-path fading. Here a copy of length L called guide time of the previous symbol is placed as a prefix of the new input. The N parallel outputs of the cyclic prefix insertion stage are then converted to serial form thereby forming the based band signal that is then converted to upward frequency by carrier signal for radio transmission [7][4].

At the receiver side, a carrier frequency is used to down-convert the transmitted signal to extract the baseband signal and the reversal of every stage of processing done in the transmit part is carried out and eventual the original binary bits transmitted are extracted by decoding by removing the bit(s) used in the encoding stage.

3. Applications of Orthogonal Frequency Division Multiplexing

Orthogonal Frequency Division Multiplexing scheme is used in 802.11 WLAN (this will be discussed extensively in the next section) [9] and in 3GPP Long Term Evolution where six-channel bandwidths are used (1.4MHz,3MHz,5MHz,10MHz,15MHz and 20MHz), symbol duration is 66.7μs hence consecutive sub-carriers are separated by 15KHz(1/T). The 5G technology is driven by OFDM as well with reduced latency in the range of 8ms and data throughput up to 20Gbit per second [10].

3.1. Wireless LAN (IEE 802.11A)

Wireless LAN IEEE 802.11a, uses 20MHz bandwidth in the 5GHz frequency spectrum. OFDM is also used in a later version of IEEE 802.11ac which uses a much larger bandwidth (80 or 160MHz) and could deliver a maximum data rate close to 7Gbps [9].

The symbol duration T of 802.11a standard is 3.2μs (with symbol interval time T_{sym} of 4μs) and thus implies that the subcarriers to be used are: -

$$\frac{\pm \mathrm{k}}{\mathrm{T}}=\pm 313.5\mathrm{KHz},\ \pm 625\mathrm{KHz}\ \ldots$$

The 20MHz is divided into 64. From the available 64 subcarriers having $k = [-32 \ldots\ldots\ldots +31]$ only 48 subcarriers from indexes range of -26 to +26 are used for transmission of data, while 12 subcarriers are zeroed to minimize adjacent channel interference. The remaining 4 subcarriers with indexes $-21, -7, +7$ and $+21$ are used as pilot symbols for channel estimation and synchronization(3)[3].

Each symbol transmitted consists of both the cyclic prefix and the data. For the error correction code, three rates are used ($r = 1/2, 2/3$ *or* ¾).

In IEEE 802.11a, the minimum data throughput occurs when BPSK (1 bit/symbol) and code rate ½ are used and only 48 subcarriers transmit data.

$$Data\ rate = No.of\ subcarriers * Bits\ per\ Symbol * code\ rate * 1/T_{sym}$$

Minimum data rate:

$$= 48\ subcarriers * 1 * \frac{1}{2} * \frac{1}{4 * 10^{-6}} = 6Mbps$$

For the maximum data rate which corresponds to r=3/4 and 64QAM.

Maximum data rate:

$$= 48\ subcarriers * 6 * \frac{3}{4} * \frac{1}{4 * 10^{-6}} = 54Mbps$$

4. Review of Advances in OFDM

This section entails a brief review of some related research works on advancement in orthogonal frequency-division multiplexing (OFDM) which have been investigated and published by researchers.

According to Gebremicael et al [10], who researched comparing filter bank multi-carrier (FBMC) and OFDM radio-frequency power amplifier(RFPA) linearization requirement, the advent of wireless technology standards were drastically increasing in demand for high linearity from the power amplifier (PA). They posited that success in wideband messaging needs the PA to work in concurrent multiband operation with power added efficiency (PAE) increased. They examined FBMC and its effect on the PA characteristic model. Also, measurement was done with a narrow and wideband FBMC signal. It was noted from the results that the PA displayed memory impact despite having narrow band operations. The crest factor of the input signal was raised by the simultaneous multi-band operation. It was concluded that a better adjacent channel leakage ratio (ACLR) performance was achieved with digital pre-distortion (DPD) applied to the OFDM signal at an increased polynomial complexity in comparison to DPD results in the FBMC signal.

Xiang et al [11], worked on a two-band optical-OFDM with an adaptive cyclic prefix. They stated that in data centre networks (DCN), optical fibre messaging was easily developed [6]. Adaptively modulated-OOFDM (AMOOFDM) was considered the most prospective technique for activating a high-velocity and cheap transceiver in DCN. They added that this technique of dual-band AMOOFDM exhibits conventional AMOOFDM, combining the adaptive cyclic prefix (ACP) and the advantages of subcarrier modulation (SCM). Xiang concluded that AMOOFDM could uplift the dispersion tolerance, flexibility and robustness of the network through the use of ACP and conveniently explore the frequency response of the transmission link over the baseband.

In [12], Tehrani and Yeh investigated space-time parallel cancellation (STPC) OFDM in power line communications (PLC). They simulated space-time (ST) and STPC-OFDM systems in a 15-channel linear time-variant (LTV) path modelling. In addition, it was discovered that bit error rate (BER) results of STPC-OFDM systems gotten from wireless research were better than that of ST-OFDM. Tehrani concluded that the system having a greater number of subcarriers exhibits a far better bit-error-rate (BER) resulting in a PLC multichannel fading path.

Nakao and Sugiura [13], examined a spectrally efficient FDM (SEFDM) with index-modulated non-orthogonal subcarriers. A new integration of SEFDM and index modulation (IM) schemes that were able to reduce the negative impact of inter-carrier interference, thereby allowing them to operate in a high-subcarriers scenario, was postulated. They summarized that their SEFDM-IM proposed scheme was better than the existing OFDM and SEFDM techniques in certain low-rate cases.

Also, Kamali in [14], researched OFDM and multiple access (MA). He reviewed the basic techniques of OFDM signalling as a representation of an efficient principle for signal transmission over frequency-selective fading paths. More so, the cogent characteristics of coded-OFDMA (COFDM) were extensively analyzed. Application areas of COFDM in IEEE 802.11 standard-based wireless LAN and digital voice broadcast (DVB) were elucidated. Kamali concluded that scalable OFDMA (SOFDMA) forms the building block over which the physical layer protocols of mobile AeroMACS and WiMAX topologies are built.

In [15], Knill et al investigated random multiplexing for Multiple-input, multiple-output orthogonal frequency-division multiplexing (MIMO-OFDM) radar using shrunk sensing-based rebuilding. This paper presented a haphazard MIMO technique for OFDM supported by a multi-dimensional compressed sensing (CS) approach that used the intertwined data of all paths to restore effectively missing signal samples. Knill used measurements of experimental OFDM radar to validate the processing. It was concluded that during the CS rebuilding, the angle of data of the paths was preserved, including the unbiased velocity and range of the complete OFDM.

Jang and Sikander in [16], worked on cooperative cognitive (CC) systems with OFDM and frequency hopping (FH). They proposed an experimental actualization of CC radio, with OFDM for the primary user (PU) and FH for the cognitive user (CU), which showed that the interference was eradicated after synchronization. It was concluded that the efficiency of both PU and CU diminished for nonzero OFDM frequency offset.

The Orthogonal Frequency Division Multiplexing has a good number of advantages and likewise disadvantages which are enumerated below.

4.1. Advantages of OFDM

- Efficient utilization of frequency spectrum i.e. can accommodate more carriers within a bandwidth compared to Frequency Division Multiplexing.
- Ability to cope with intersymbol interference (IS) or inter-block interference (IBI) and fading due to multipath propagation [6].
- Efficient implementation of several modulators and demodulators using fast Fourier transform.
- It has low sensitivity to time synchronization errors.

4.2. Disadvantages of OFDM

- High peak-to-average ratio (PAPR) [17][2].
- Sensitive to frequency offset, hence to Doppler-shift as well[2].
- Cyclic prefix/guard interval causes loss of efficiency

5. Conclusion

OFDM will continue to be a relevant technology due to its efficient utilization of the spectrum and hardware optimization by the realization of multiple modulators and demodulators via Fourier transform and Inverse Fourier transform. Apart from the 4G or Long-Term Evolution and Wi-Fi 802.11a being driven by OFDM, it is still the core of the 5G technology which has much higher data throughput up to 20G bps and low latency in the range of 8ms which will unlock numerous potentials around IoT, Artificial Intelligent, Big Data and Cloud services.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflicts of interest.

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