OFDM MODULATION FOR 4G LTE MOBILE

ID: 20493425
DEGREE: MSC ELECTRONIC COMMUNICATIONS AND COMPUTER ENGNEERING

MODULE: MOBILE TECHNOLOGIES EEEE3087

Table of Contents

PART 1

Question 1

Orthogonal Frequency-Division Multiplexing (OFDM) is a modulation technique that divides the existing bandwidth into several spaced orthogonal subcarriers which are narrowband signals, each modulated with a low data rate stream. The number of subcarriers can be between below hundred to thousands and a spacing of hundred KHz to fewer KHz. OFDM uses single carrier modulations like and Quadrature Amplitude Modulation (QAM) to get comparable data rates in transmission by choosing data symbols from a constellation. This leads to high spectral efficiency, robustness against multipath fading, and flexibility in allocating resources. It is a digital multi-carrier multiplexing scheme used in modern wireless communication systems, such as 4G LTE networks providing high-speed and low latency. The spacing for this LTE is 15kHz with 600 subcarriers in 10MHzspectrum. [1] [2]

The evolution of mobile networks from the first cell phones (1G) began in the 1970s. They were large, expensive, and mostly limited to car phones and briefcase-sized portable devices. The first available cell phone was the Motorola DynaTAC 8000X and was released in 1983. Then came the Analog cellular systems in the1980s such as include the Advanced Mobile Phone System (AMPS) in North America, the Nordic Mobile Telephone (NMT) in Scandinavia, and the Total Access Communication System (TACS) in the United Kingdom. These systems allowed voice communication but was limited and were prone to eavesdropping. 2G came around in the 1990s. 2G introduced digital technology and improved voice quality and security. The primary 2G technologies were the Global System for Mobile Communications (GSM) and Code Division Multiple Access (CDMA). The IS-54 and IS-136 standards were used digital technologies used before CDMA and GSM got more popular. 3G was used in the early 2000s and provided faster data transfer rates. The technologies were General Packet Radio Service (GPRS), Wideband Code Division Multiple Access (WCDMA), High-Speed Downlink Packet Access (HSDPA), and High-Speed Uplink Packet Access (HSUPA). The IEEE 802.16 (WiMAX) was also developed during this period as an alternative to cellular networks for wireless broadband access. 4G was made in the late 2000s-2010s and it provided even higher data transfer rates, lower latency, and better connectivity. The primary technology for 4G was Long-Term Evolution (LTE). This allowed for high-definition video streaming and faster and more efficient data transmission. [2] [3]

OFDM Implementations

1. DVB-T

Digital Video Broadcasting – Terrestrial (DVB-T) uses COFDM (Coded Orthogonal Frequency-Division Multiplexing) as its modulation scheme, which is a variant of OFDM that includes forward error correction (FEC) coding to better the robustness against channel impairments. DVB-T has been adopted in many countries as the go-to for digital terrestrial television and replacing analog television systems. It offers better image and sound quality and the ability to transmit multiple programs simultaneously on the same frequency channel. OFDM enabled more efficient use of the radio spectrum which is why DVB-T replaced analog broadcasting systems as networks evolved from 3G to 4G. [4]

2. WiMAX

Worldwide Interoperability for Microwave Access (WiMAX) is a wireless broadband communication standard based on IEEE 802.16 which uses OFDM for efficient data transmission. WiMAX provides high-speed internet access and multimedia services over long distances and there are two versions of it:

a. IEEE 802.16-2004 (Fixed WiMAX): This provides fixed broadband wireless access, for last-mile connectivity and wireless backhaul. Fixed WiMAX uses OFDM with 256 subcarriers for data transmission.

b. IEEE 802.16e-2005 (Mobile WiMAX): This is the supplement to the Fixed WiMAX to support mobility, enabling users to access high-speed Internet services while on the move. Mobile WiMAX uses Scalable OFDMA (SOFDMA), a variation of OFDM that allows for flexible and scalable bandwidth allocation.

With the increase in demand of LTE and 5G networks, WiMAX's demand has decreased in recent years. [5]

3. Single-Carrier Frequency Division Multiple Access (SC-FDMA)

SC-FDMA is the uplink transmission multiple access technique for 4G LTE networks. It combines OFDM with single-carrier modulation to reduce the peak-to-average power ratio (PAPR), leading to better power efficiency and longer battery life for mobile devices. SC-FDMA is used for its reduced PAPR, efficient frequency-domain equalization, and low sensitivity to carrier frequency offsets. The LTE downlink uses OFDM, while the uplink uses SC-FDMA. This is considered a variant of OFDM as well. [6]

4. WLAN

WLAN (Wireless Local Area Network) is a wireless networking technology that uses OFDM as its primary modulation scheme. Ethernet is the standard LAN for wire and cable use. The most used WLAN standard is IEEE 802.11, which specifies several sub-standards, including 802.11a, 802.11b, 802.11g, 802.11n, 802.11ac and 802.11ad. Each of these sub-standards uses OFDM in slightly different ways. 802.11a operates in the 5 GHz frequency band and uses 52 subcarriers, each with a spacing of 312.5 kHz at data rates 54Mbps. 802.11b is the slowest and cheapest, also known as wireless Ethernet. 802.11g operates in the 2.4GHz frequency band. 802.11n uses 64 subcarriers and employs a technique called multiple-input multiple-output (MIMO) to increase data.[2]

5. ADSL

ADSL (Asymmetric Digital Subscriber Line) is a broadband communication technology that uses OFDM to transmit data over copper telephone lines. ADSL uses a technique called frequency-division duplexing (FDD), which allows simultaneous transmission and reception of data on separate frequency bands. ADSL has several sub-standards: ADSL, ADSL2, and ADSL2+, which uses OFDM in slightly different ways. For example, ADSL2+ uses 256 subcarriers, each with a spacing of 4.3125 kHz, to achieve data rates of up to 24 Mbps downstream and 1.4 Mbps upstream [7].

Variants of OFDM

1. Discrete Fourier Transform Spread OFDM (DFT-SOFDM)

DFT-SOFDM is a variant of OFDM that reduces PAPR by spreading the data symbols over several subcarriers using a discrete Fourier transform (DFT) pre-coding. DFT is passed through an inverse fast Fourier transform (IFFT) to generate the time-domain waveform. This implementation is for downlink transmission in 4G LTE networks, giving improved performance under frequency-selective fading conditions and multipath propagation [8].

2. Multi-User MIMO OFDM

Multi-User Multiple Input Multiple Output (MU-MIMO) is an advanced antenna technique that is an extension of OFDM. It allows simultaneous data transmission to multiple users by exploiting spatial diversity. This enhances the channel capacity of 4G LTE networks by enabling better use of available radio resources and using multiple antennas at both the transmitter and receiver. MU-MIMO is used in both uplink and downlink transmission in 4G LTE networks. [2]

3. Cyclic Prefix OFDM (CP-OFDM)

CP-OFDM is a variant of OFDM that adds a cyclic prefix (CP) to the OFDM symbols to combat inter-symbol interference (ISI) and inter-carrier interference (ICI) caused by multipath fading channels. This is done by providing a guard interval. The cyclic prefix is a copy of the last part of the OFDM symbol, which is added at the beginning of the symbol. CP-OFDM is employed in various wireless and wired communication standards, such as LTE, Wi-Fi, and DVB-T. OFDM’s role in 4G and its evolution from 3G is marked using CP-OFDM as a key technology to improve performance in multipath fading environments and its ability to significantly reduce the use of ISI and ICI makes CP-OFDM known. [9]

Question 2

DVB-T is used for broadcasting digital television signals over terrestrial networks using OFDM, COFDM and to allow for various transmission speeds the non-differential modulation schemes: 16-QAM, 64-QAM and QPSK are used. The spacing for this LTE is 8MHz. All this together is for efficient and robust transmission of digital TV signals. [4]

Operating Principles:

DVB-T operates by transmitting digital data as a series of OFDM symbols. The input data can then be divided into high and low priority data streams with varying error protection purposes with uniform or non-uniform mapping rules, which are then modulated onto separate subcarriers. These subcarriers are orthogonal to each other, which means they do not interfere with one another, even though they are closely spaced in the frequency domain. QAM modulates the data onto the subcarriers. It is a modulation scheme that combines both amplitude and phase modulation to convey information. To prevent interruptions caused by interference from echoes or neighbouring transmitter signals in SFNs, a guard interval is added between successive OFDM symbols. If the guard interval is increased without changing the useful interval, the channel capacity and bitrate decreases. Longer guard intervals are used for networks with further distances. This leads to efficient use of bandwidth, higher data rates, reduces the likelihood of inter-symbol interference (ISI) which causes distortion and limits data rates and increases the system's robustness to multipath fading. [4]

Modulator Design: The DVB-T modulator consists of the following main blocks [10]:

1. Source coding and channel coding: The digital TV signal is compressed and encoded using source coding techniques such as MPEG-2 and H.264 and channel coding techniques like convolutional coding and Reed-Solomon coding to reduce the bit rate and protect against transmission errors. The correction can be to a maximum of 8 incorrect bytes for each 188-byte packet.
2. Bit interleaving (external and internal): The external interleaving uses convolutional interleaving to reorganise the transmitted data sequence and the internal interleaving uses block interleaving with a pseudo-random assignment scheme to reorganise the data sequence again to further protect against burst errors.
3. QAM modulation: The interleaved data is mapped onto QAM symbols according to the chosen QAM constellation.
4. OFDM modulation: The QAM symbols are modulated onto the orthogonal subcarriers using an Inverse Fast Fourier Transform (IFFT).
5. Guard interval insertion: A cyclic prefix is added to each OFDM symbol to mitigate inter-symbol interference caused by multipath propagation [2]. The width of the guard interval can be 1/32, 1/16, 1/8, or 1/4, of the original block length. The IFFT output vector Xn is added to cyclic suffix to get $X_{(n,m)} = A\sum X_{n,k} * e^{(j2\pi km/N)}$ [12]
6. RF up-conversion: The baseband OFDM signal is up-converted to the desired RF frequency and transmitted over the air. [10]

Demodulator Design: The DVB-T demodulator performs the inverse operations of the modulator [10]:

1. RF down-conversion: The received RF signal is down-converted to baseband then transformed to a digital signal.
2. Guard interval removal: The cyclic prefix is removed from each OFDM symbol.
3. OFDM demodulation: The OFDM symbols are demodulated using a Fast Fourier Transform (FFT) to recover the QAM symbols.
4. QAM demodulation: The QAM symbols are demapped to recover the interleaved data.
5. Bit deinterleaving: The data is deinterleaved to reconstruct the original encoded data.
6. Channel decoding and source decoding: The encoded data is decoded using channel decoding techniques such as Viterbi decoding and Reed-Solomon decoding and source decoding techniques like the MPEG-2, H.264 decoding to recover the original digital TV signal. [10]

Advantages of using QAM+OFDM in DVB-T:

1. High spectral efficiency as QAM and OFDM allow for efficient use of bandwidth, enabling more channels to be transmitted in each frequency band.
2. DVB-T requires lower transmission power compared to other systems.

3. They are less affected by interference compared to analogue signals.
4. DVB-T is flexible as it supports multiple modulation and coding schemes, allowing adaptive modulation, and coding depending on the channel conditions and it allows convergence TV. [11]

Disadvantages of using QAM+OFDM in DVB-T

1. OFDM systems are sensitive to Doppler shift caused by high-speed mobility, which can cause inter-carrier interference.
2. Synchronization and channel estimation are essential for the proper functioning of the OFDM system, but they are computationally complex and challenging in real-world scenarios.
3. The need for guard intervals, which reduces spectral efficiency.
4. Complexity in implementing FFT algorithms.

Analysis of QAM+OFDM in DVB-T

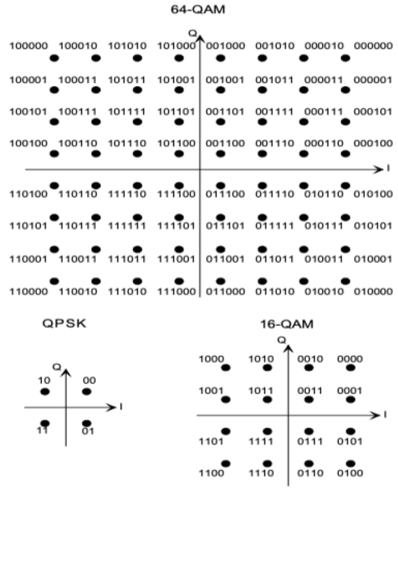
The OFDM system can be calculated using this equation:
s(t) = A∑b(t-nT,Xn), where s(t) is the time-domain signal at time t and A, the amplitude scaling factor of the signal. The equation b(t,xn) = uT(t) * xn,k * e^(j2πkt/T) is the equation showing the conversion of each frequency-domain symbol xn,k to the time-domain subcarrier waveform b(t,xn) using the pulse shape uT(t), and the exponential term e^(j2πkt/T) to change the subcarrier from the frequency domain to the time domain. [12]

The net deliverable data rate in DVB-T depends on the inner and outer coding, the net bit rate depends on the carrier modulation method, and the guard interval length. The net data rate is calculated using this formula:
RU = RS × b × CRI × CRRS × (TU/TS);
Where RU is the useful net data rate (Mbit/s), RS is the symbol rate, 6,75 Msymbols/s, b is the bits per carrier, CRI is the inner code rate, CRRS is the Reed Solomon code rate (188/204), TU is the duration of symbol part; TS is the symbol duration, including guard interval. [11]

The Bit Error Rate (BER) of a QAM+OFDM system gives an approximation of the bit error probability [13]. BER depends on the choice of QAM constellation, channel conditions, and system design. BER curves for QAM+OFDM systems show that higher-order QAM schemes have a higher error rate but can achieve higher data rates. For instance, a higher-order QAM scheme like 256-QAM will give a higher data rate but may also have a higher bit error rate (BER) because of increased sensitivity to noise and interference. A lower-order QAM scheme such as 16-QAM will have a lower data rate but a better BER performance.

QAM constellations show the combination of amplitude and phase values for a QAM scheme. For example, a 16-QAM constellation has 16 points, each corresponding to a unique combination of amplitude and phase values. The distance between constellation points determines the system's tolerance to noise and interference. Higher-order QAM schemes have more closely spaced points, resulting in a higher data rate but also increased sensitivity to noise. The QAM equation is: I(t) = A(t) * cos(2πfct + θ(t)) where A is the amplitude, fc is the subcarrier frequency, θt is the phase of the modulated signal. [14].

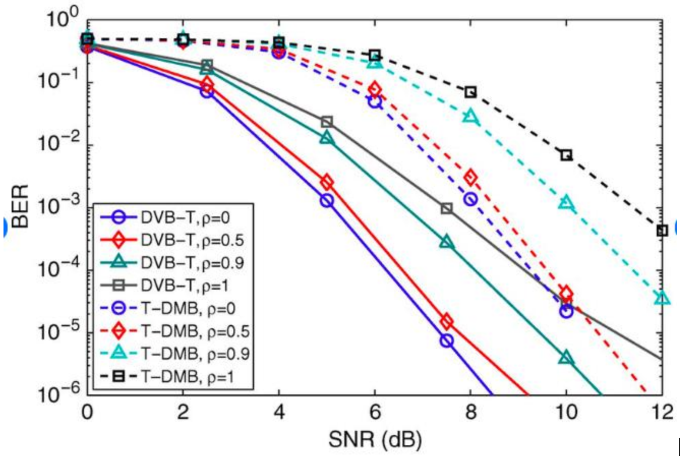
Figure 1 showing the constellation diagram for 64-QAM, 16-QAM and QPSK which are used as the modulation methods in DVB-T



[4]

BER curves for QAM+OFDM systems can be obtained through simulations, with these factors: modulation order, signal-to-noise ratio (SNR) and channel conditions.

Figure 2 showing the BER performance of DVB-T at 8 MHz with r = 1=2 and T-DMB (DAB) with r = 2=3 at the output of the Viterbi decoder, for two receive antennas. Rayleigh BU channel, f = 800Mhz, v = 300Km/h (f = 0:038 for T-DMB, f = 0:050 for DVB-T) [15]



[15]

Question 3

The practical implementation of an OFDM modulator in DVB-T uses a combination of microcontrollers, FPGAs, and CMOS components. The microcontrollers can be used to control the overall system operation, manage communication between functional blocks, and configure the modulator parameters like modulation scheme, IFFT size, and cyclic prefix length.
FPGAs are used to implement digital logic circuits for the bit allocation, constellation mapping, serial-to-parallel conversion, IFFT, cyclic prefix insertion, and parallel-to-serial conversion. FPGAs provide the flexibility to implement and optimize the design for different modulation schemes and IFFT sizes used in DVB-T.
High-speed DACs and RF upconversion mixers can be designed using CMOS technology to convert the digital signal into an analog RF signal. The modulator's overall size and power usage are reduced thanks to the integration of numerous components onto a single chip made possible by CMOS technology. [16]

Explanation of how the simple schematic diagram of the OFDM modulator is mapped onto practical components and circuits [16]:

1. Digital logic circuits or lookup tables implemented in FPGAs are used to convert input data bits into the corresponding constellation symbols.
2. Shift registers designed using flip-flops convert the serial input data into parallel data streams.
3. DSP processors, ASICs, or FPGAs can be used to perform the IFFT operation.
4. Digital logic circuits or FPGA-based implementations are used to insert the cyclic prefix into the time-domain signal.
5. Shift registers designed using flip-flops convert the parallel data streams with cyclic prefixes into a serial format.
6. A high-speed DAC and an RF upconversion mixer can be used to convert the digital signal into an analog RF signal. [16] To have the same input data rate with a cyclic guard, this must have a higher frequency. [12]

There is the presence of Additive White Gaussian Noise (AWGN) in the signal during processing. The signal is sent via a terrestrial transmission link, which involves multi-path reception with reflections, AWGN and doppler effects causing several echo paths. [11]

PART 2

Using 16-QAM modulation, the effect of Additive White Gaussian Noise (AWGN) can be evaluated by analysing the system's performance at different Eb/No values.

Using these Simulink blocks below, this can be achieved [16]:

1. Random Integer Generator: Generates serial binary data that will be transmitted to the serial parallel converter.
2. Rectangular QAM Modulator Baseband: Modulates the generated integer values using the QAM modulation scheme. The output is a complex baseband signal, which is a combination of the in-phase and quadrature components.
3. Reshape: Reshapes the modulated signal into a matrix form, where each row represents one OFDM symbol.
4. Pad: Pads the reshaped signal with zeros to get the desired size for the IFFT operation. This is done to maintain orthogonality in subcarriers in OFDM.
5. IFFT Block: Performs the IFFT operation on each OFDM symbol (row of the matrix). This transforms the signal from the frequency domain to the time domain. The output gives samples of modulated multiplexed signal. [2]
6. Gain: Applies a gain factor to the time-domain signal to adjust the power level of the transmitted signal. It normalises (sqrt (64)) the gain value of the subcarriers or de-normalises (1/sqrt (64)) the power of the sub-carriers.
7. Selector: Selects required parameters for simulation.
8. AWGN Block: Simulates the communication channel by adding white Gaussian noise to the transmitted signal, representing the channel noise and impairments.
9. FFT: Transforms the received noisy signal from the time domain back to the frequency domain for each OFDM symbol.
10. To Frame Block: Converts the frequency-domain signal back into a matrix form, where each row represents one OFDM symbol.
11. Error Rate Calculation: Compares the demodulated QAM symbols with the original transmitted symbols and calculates the error rate for the received data.

[16]

Table showing BER, EVM and MER results with change in Eb/No

Eb/No	0	5	10	15	20	25
Bit Error Rate	0.7412	0.5374	0.2219	0.0178	1.12e-05	0
Bits Received	2.847e+06	2.064e+06	8.525e+05	6.839e+04	43	0
Bit Transmitted	3.841e+06	3.841e+06	3.841e+06	3.841e+06	3.841e+06	3.841e+06
RMS EVM (%)	52.38	33.10	26.40	16.32	9.27	5.21
Peak EVM (%)	150.72	84.75	69.96	31.79	22.12	12.44
Avg EVM (dB)	-5.62	-9.60	-11.57	-15.75	-20.66	-25.66
Peak EVM (dB)	3.56	-1.44	-3.10	-9.95	-13.10	-18.10
Avg MER (dB)	6.23	9.53	11.96	15.88	20.86	25.69

Important Parameters that affect OFDM:

The number of subcarriers determines the frequency spacing between adjacent subcarriers and the overall system bandwidth. Increasing the number of subcarriers improves frequency efficiency and system capacity but also increases the computational complexity.
The choice of modulation scheme (BPSK, QPSK, QAM, etc.) affects the data rate and the robustness of the system. Higher-order modulation schemes allow for increased data rates but are more susceptible to noise and interference. [17]

The length of the cyclic prefix is critical for mitigating inter-symbol interference and maintaining orthogonality between subcarriers [12]. A longer cyclic prefix provides better protection against ISI but reduces the useful data rate, as more time is spent transmitting unnecessary information.
The subcarrier spacing determines the orthogonality between subcarriers and the susceptibility of the system to frequency-selective fading. Smaller subcarrier spacing reduces the effect of frequency-selective fading but increases the symbol duration. [18]

The choice of channel coding scheme and coding rate affects the overall data rate and error performance. Bit synchronization ensures the receiver correctly interprets the transmitted data bits with the right parameters. [10]

The purpose of the 'number of bits per symbol' parameter in the AWGN block is to define the modulation scheme used. For example, in the 16-QAM modulation used to get the table above, there are 16 different symbols, each representing 4 bits. This parameter determines the relationship between the energy per bit (Eb) and the energy per symbol (Es).

The 'symbol period' parameter defines the duration of each transmitted symbol. The symbol period is the inverse of the symbol rate and determines the bandwidth of the transmitted signal.

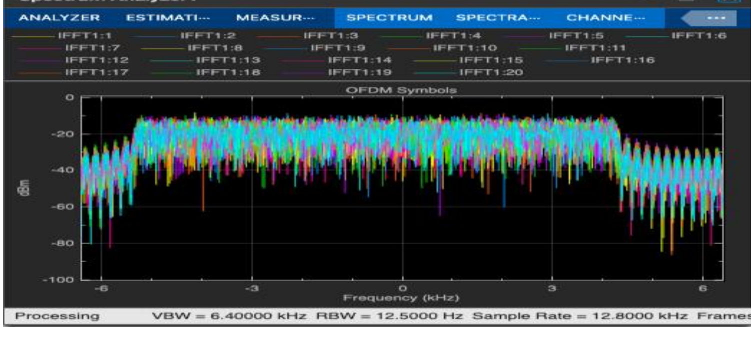
The results above show that as the Eb/No increases, the bit error rate (BER) decreases. This shows that the system performs better with higher Eb/No values, as the signal-to-noise ratio (SNR) improves. The received signal constellation became more distinct with higher Eb/No values, resulting in lower error rates as shown in figures 4, 5, 6, 7, 8 and 9 below. The error vector magnitude (EVM) values in RMS, Peak (in %), Avg, and Peak (in dB) decreases as Eb/No increases, resulting in better modulation error ratio (MER) as the table shows it increasing with increase in Eb/No. This means there is better signal quality.

Removing the OFDM blocks and using QAM modulation alone, will lead to performance degradation, in multipath fading channels. QAM modulation without OFDM will be more prone to ISI because the symbols overlap in time, and the system will lose its robustness against frequency-selective fading. [19]

When comparing QAM and QAM+OFDM systems in the presence of Rayleigh fading, OFDM can provide a more robust performance. Due to its multicarrier nature, OFDM can combat frequency-selective fading more efficiently. In QAM systems without OFDM, frequency-selective fading can cause deep fades in the received signal, significantly affecting the BER [19].

In comparing BER results between QAM and QAM+OFDM systems, it has been observed that the OFDM system performs better than the QAM system, especially in multipath fading environments. The BER decreases more rapidly with increasing Eb/No in the OFDM system, stressing its resilience against ISI and fading.

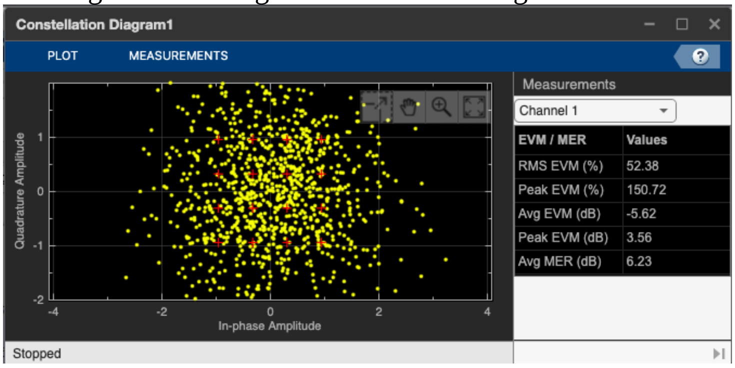
Figure 3 showing the spectrum analyser diagram which shows the signals frequency content



Discussion of Results

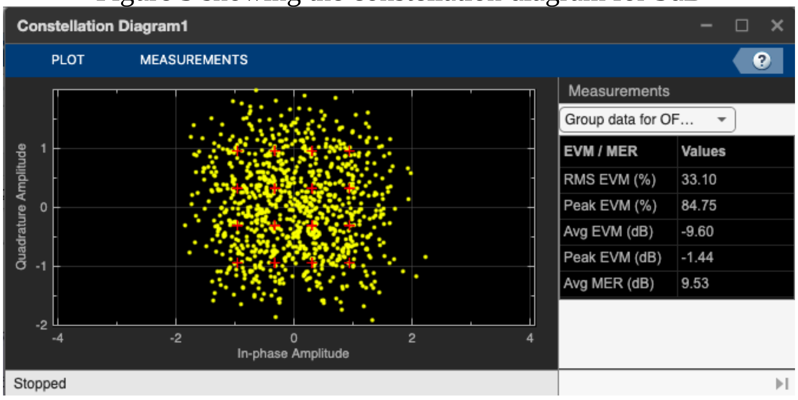
At Eb/No 0dB, the noise is very strong compared to the signal energy. The system experiences a high BER (0.7412) due to the presence of strong noise. The constellation points shown are dispersed and far from their ideal positions as seen in Figure 4 below, leading to a high probability of symbol errors.

Figure 4 showing the constellation diagram for 0dB



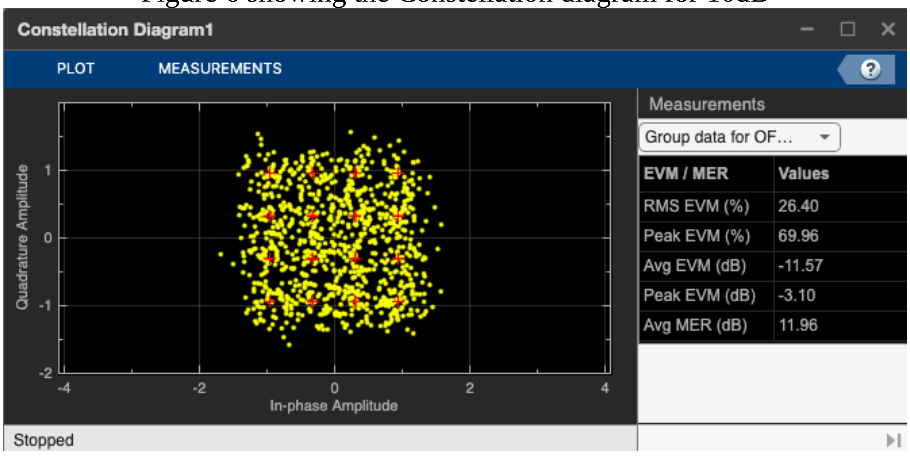
At 5dB, the Eb/No has increased and the noise power decreases relative to the signal power. The BER (0.5374) is lower compared to the 0 dB, but there will still be a significant number of symbol errors due to the remaining noise. Figure 5 below shows the constellation points heading closer together than in figure 4 above.

Figure 5 showing the constellation diagram for 5dB



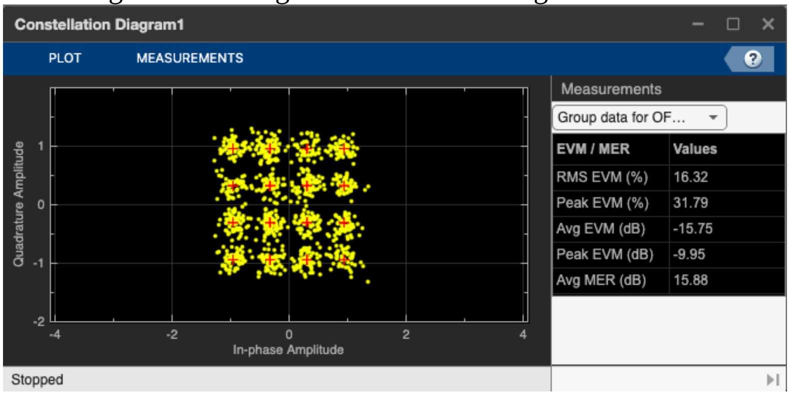
At 10dB there is a further increase in Eb/No, therefore the noise power continues to decrease. The BER (0.2219) is lower than the previous two cases as seen on the table above and the received constellation points are closer to their ideal positions as seen in Figure 6 below. However, some symbol errors will still occur due to the noise.

Figure 6 showing the Constellation diagram for 10dB



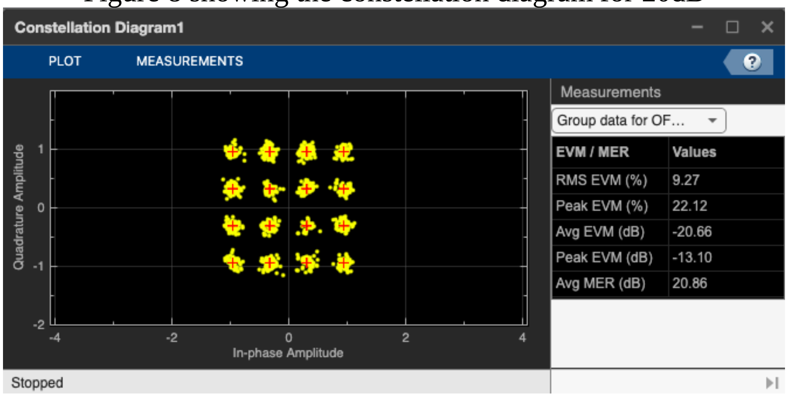
At 15dB, the system performance improves significantly. The BER (0.0178) is much lower than the previous cases, and the received constellation points are closely clustered around their ideal positions, leading to fewer symbol errors as shown in Figure 7 below.

Figure 7 showing the constellation diagram for 15dB



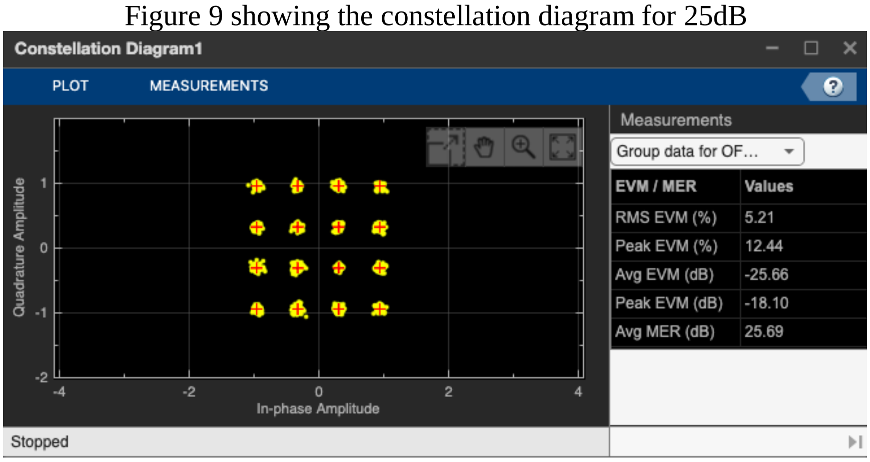
At 20 dB, the noise power is very low compared to the signal power. The BER (1.12e-05) is extremely low and has experienced a significant drop, and the constellation points are almost indistinguishable from their ideal positions. Symbol errors will be rare.

Figure 8 showing the constellation diagram for 20dB



At 25 dB, which is an extremely high Eb/No, the noise power is negligible (0) compared to the signal power. The system performance is close to ideal, with an extremely low BER and almost perfect received constellation points.

Figure 9 showing the constellation diagram for 25dB



Conclusion

In conclusion, Orthogonal Frequency-Division Multiplexing (OFDM) has proven to be a highly effective modulation technique for modern wireless communication systems. With its ability to combat the detrimental effects of multipath fading and inter-symbol interference, OFDM has become the basis of various digital communication standards, including DVB-T for digital television broadcasting.

The comparison between QAM and QAM+OFDM systems demonstrated the advantages of incorporating OFDM into the modulation scheme. OFDM's multicarrier nature, with the adaptive modulation and channel coding, contributes to its robustness and adaptability to different channel conditions. The results obtained from the original tests performed with the Simulink model in the presence of multi-path fading blocks further support the superiority of OFDM-based systems, as the BER performance improves significantly with increasing Eb/No values.

While OFDM offers numerous benefits, it is not without challenges. The sensitivity to Doppler shift, high peak-to-average power ratio (PAPR), and the need for accurate synchronization and channel estimation are among the factors that need to be addressed for optimal performance. Nonetheless, the development of advanced signal processing techniques and continued research in this is expected to enhance the performance of OFDM-based systems.

In summary, OFDM will still be in the future of wireless communication, providing more reliable and efficient methods of transmitting data in increasingly crowded and complicated communication environments. As the demand for high-speed, low-latency, and seamless connectivity continues to grow, OFDM plays a role in meeting these requirements and shaping the future of wireless communication.

Reference:

[1] What is OFDM? (no date) What Is OFDM? - MATLAB & Simulink. Available at: https://uk.mathworks.com/discovery/ofdm.html (Accessed: March 29, 2023).

[2] “EEEE3087 Mobile Technologies Lecture 10-E01: 4G and WIFI” (no date). Nottingham: University of Nottingham.

[3] *History of mobile phones* (2023) *Wikipedia*. Wikimedia Foundation. Available at: https://en.wikipedia.org/wiki/History_of_mobile_phones (Accessed: March 29, 2023).

[4] *TR 103 593 - V1.1.1 - System Reference Document (SRdoc ... - ETSI* (no date) *TR 101 190 -V1.2.1 - Digital Video Broadcasting*. Available at: https://www.etsi.org/deliver/etsi_tr/103500_103599/103593/01.01.01_60/tr_103593v010101p.pdf (Accessed: March 29, 2023).

[5] *WiMAX* (2022) *Wikipedia*. Wikimedia Foundation. Available at: https://en.wikipedia.org/wiki/WiMAX (Accessed: March 29, 2023).

[6] Myung, H. G., Lim, J., & Goodman, D. J. (2006). Single carrier FDMA for uplink wireless transmission. IEEE Vehicular Technology Magazine, 1(3), 30-38.

[7] International Telecommunication Union, "Asymmetric digital subscriber line (ADSL) transceivers," ITU-T G.992.1, 1999.

[8] ANNUR, R.O.B.I.T.H.O.H. (2010) *LOCALIZED DISCRETE FOURIER TRANSFORM SPREAD OFDM (DFT-SOFDM) SYSTEMS FOR 4G WIRELESS COMMUNICATIONS*. thesis.

[9] Notes, E. (no date) *OFDM cyclic prefix, CP-OFDM, Electronics Notes*. Available at: https://www.electronics-notes.com/articles/radio/multicarrier-modulation/ofdm-cyclic-prefix-cp.php (Accessed: March 29, 2023).

[10] *DVB-T* (2023) *Wikipedia*. Wikimedia Foundation. Available at: https://en.wikipedia.org/wiki/DVB-T (Accessed: March 29, 2023).

[11] Gupta, S., Ritika and Sanjeev (2015) *Digital Video Broadcasting (DVB): Architecture, Applications, benefits and Design*, 2(5). Available at: http://ijcem.in/wp-content/uploads/2015/09/Digital-Video-Broadcasting-DVB-Architecture-Applications-benefits-and-Design1.pdf (Accessed: March 29, 2023).

[12] “EEEE3087 Mobile Technologies Lecture 4-E04: Multi-carrier Modulation Schemes” (no date). Nottingham: University of Nottingham.

[13] “EEEE3087 Mobile Technologies Lecture 4-E03: Errors in Digital Modulation Schemes” (no date). Nottingham: University of Nottingham.

[14] *What is QAM? quadrature amplitude modulation overview* (no date) *NI*. Available at: https://www.ni.com/en-gb/innovations/white-papers/06/quadrature-amplitude-modulation--qam-.html#:~:text=I%20%3D%20A%20cos(%CF%86),%3D%20A%20sin(%CF%86).&text=A%20cos(2%CF%80fct%20%2B%20%CF%86)%20%3D%20I%20cos,amplitude%20of%20I%20and%20Q. (Accessed: March 29, 2023).

[15] Banelli, P. (no date) *Fig. 12. BER performance of DVB-T at 8 MHz with R = 1=2 and T-DMB (DAB)..., researchgate.net*. Available at: https://www.researchgate.net/figure/BER-performance-of-DVB-T-at-8-MHz-with-r-12-and-T-DMB-DAB-with-r-23-at-the-output_fig7_220020930 (Accessed: March 29, 2023).

[16] Gutiérrez , F.M. (2009) *Implementation of a Tx/Rx OFDM System in a FPGA , PFCvfinal*. thesis. Available at: https://upcommons.upc.edu/bitstream/handle/2099.1/6848/memoria.pdf?sequence=1&isAllowed=y (Accessed: March 29, 2023).

[17] *Understanding modern digital modulation techniques - electronic design* (2014). Available at: https://www.electronicdesign.com/technologies/communications/article/21798737/electronic-design-understanding-modern-digital-modulation-techniques (Accessed: March 29, 2023).

[18] *The key benefits and differences between OFDM and OFDMA?* (2022) *Extreme Networks*. Available at: https://www.extremenetworks.com/extreme-networks-blog/ofdm-and-ofdma-subcarriers-what-are-the-differences/#:~:text=Subcarrier%20spacing%20is%20equal%20to,and%20therefore%20enhanced%20channel%20robustness. (Accessed: March 29, 2023).

[19] Goldsmith, A. (2005). Wireless Communications. Cambridge University Press.