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Utilizing orthogonal frequency division multiple access technology to mitigate carrier and symbol interference in wireless communication networks

Nabil Abdulwahab Abdulrazaq Baban[a]

[a]Computer Engineering Techniques Department, Al-Nukhba University College, Baghdad, Iraq
**Corresponding author E-mail: nabilrazzak@yahoo.com*

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Abstract

Wireless communication networks often face challenges from carrier and symbol interference, leading to degraded signal quality and reduced data transmission efficiency. This interference occurs due to overlapping signals and multipath propagation, creating challenges in maintaining reliable communication. To address this, Orthogonal Frequency Division Multiple Access (OFDMA) technology can be utilized. By dividing the available spectrum into multiple orthogonal subcarriers, OFDMA reduces interference between symbols and carriers. However, current methods can be further improved through innovative techniques, such as dynamic subcarrier allocation, adaptive modulation, and advanced error correction algorithms, enhancing network performance and minimizing interference in diverse environments. OFDMA surpasses traditional techniques by reducing interference through orthogonal subcarriers, preventing signal overlap. Its dynamic resource allocation optimizes frequency usage, while adaptive modulation like Phase Shift Keying (PSK), and Quadrature Amplitude Modulation (QAM) adjusts to varying channel conditions. These factors collectively enhance signal quality, improve spectral efficiency, and minimize interference compared to conventional methods like FDMA or Time Division Multiple Access (TDMA). This paper introduces a novel approach to enhancing OFDMA by integrating advanced techniques like dynamic subcarrier allocation, adaptive modulation, and improved error correction. These innovations reduce carrier and symbol interference more effectively, optimize spectrum usage, and significantly improve signal quality and network efficiency in diverse wireless environments. Simulation and analysis results show the capacity of OFDMA over traditional techniques in reducing levels of interference and improving the quality of a signal. These findings underscore the great promise of OFDMA in redefining wireless communication systems further, OFDMA enables greater system performance with dynamic resource allocation under various interfering scenarios when contrasted with other methodologies like frequency reuse, adaptive filtering or adaptive power control.

Keywords: *OFDMA, ICI, ISI, IoT, PSK, QAM, ECC, MIMO, SIR, BER, SNR, LTE, FDE, TDE, CP, AMC, FFT, IFFT.*

1. Introduction

Orthogonal Frequency Division Multiple Access (OFDMA) is considered a vital technology for present-day wireless communication systems due to its high spectral efficiency, multi-user support and better robustness against interference [1]. In wireless communications, one of the most challenging challenges is to combat carrier and symbol interference which degrades the quality of a signal as well as system performance [2]. The technique of adaptive modulation in OFDMA can be considered an optimal solution approach fashioning a flexible means in combating this problem by choosing modulation schemes with dynamism based on channel conditions in real-time ensuring that both data rate and error performance are optimized [3]. This research paper investigates how OFDMA combined with adaptive modulation techniques achieves effective carrier and symbol interference mitigation for enhanced wireless communication performance [4]. A number of studies have been conducted on the improvement of interference mitigation in wireless networks; however, while Sharma et al. (2018) [5] proposed a hybrid adaptive modulation scheme for OFDMA that fights interference well enough it did not provide a strong remedy for symbol interference, Ahmed et al. (2019) [6] developed an OFDMA-based resource allocation model for ICI reduction between subcarriers, although it failed to adapt well to varying channel conditions. Chen et al. (2020) [7] introduced an OFDMA multi-user model by employing beamforming for interference reduction though with limited scalability for high-density networks. Kumar et al. (2021) [8] studied interference reduction through the use of cognitive radio with OFDMA but provided limited solutions in combating carrier interference at higher modulation levels. Patel et al. (2022) [9] proposed an OFDMA model based on the application of advanced error correction codes against interfering signals; however, the model's complexity may not permit real-time implementation. Most earlier approaches have addressed either carrier or symbol interference separately but very few have solutions toward both aspects [10]. Moreover, many such approaches are found wanting in terms of adaptability to dynamic wireless environments or have unacceptably high computational complexities [11]. This paper introduces an OFDMA system that can support an adaptive modulation technique capable of effectively mitigating both carrier and symbol interference [12]. The technical challenges in the past are overcome by providing a scalable low complexity solution which is able to adapt in real time channel conditions hence improving signal quality, data rates, and system performance [13].

2. Purpose of the study

Evaluate the OFDMA technology for counteracting Inter Symbol Interference (ISI), which is caused by non-perfectly orthogonal subcarriers in a communication system that results in signal distortion and degradation of system performance, and Inter Carier Interference (ICI), where symbols overlap in time leading to loss of symbol distinction by the receiver (at the output) which results from degraded signal quality and higher rates of errors. Examining its performance parameters towards enhancing system performance on the whole, increasing capacity as well as Quality of Service (QoS) — wherein reliable data transmission can be guaranteed comparing with discussed model OFDMA technique proves better over traditional ways such as frequency reuse, adaptive filtering or power control across key performance parameters including throughput, spectral efficiency, and lower Bit Error Rate (BER), used to indicate percentage of bits received incorrectly against total number transmitted for measuring performance/quality of a communication system.

3. Literature review

OFDMA works by breaking the available bandwidth into many orthogonal subcarriers and dividing each of these between different users by assigning unique data to each, thus allowing simultaneous transmission [14]. The orthogonality property guarantees that subcarriers will not cause any mutual interference between each other— as a result, ICI is eliminated and spectral efficiency is improved [15]. OFDMA does not allocate fixed frequency or time slots like FDMA or TDMA based on traditional methods; rather, it dynamically assigns subcarriers in order to make an optimal usage of the bandwidth [14]. Its ability to handle multiple users efficiently makes it ideal for modern wireless communication systems. OFDMA is a key technology in Long Term Evolution (LTE), WiMAX, and 5G, supporting high data rates and low latency [16]. Wireless networks face Inter-Carrier Interference (ICI), caused by frequency overlap between subcarriers, and Inter-Symbol Interference (ISI), where symbol signals overlap in time. Both degrade communication performance, lowering signal quality, reducing data rates, and increasing error rates [17]. Adaptive modulation dynamically adjusts the modulation scheme different types of Phase Shift Keying, and Quadrature Amplitude Modulation (e.g., BPSK, QPSK, QAM) based on real-time channel conditions, such as Signal-to-Noise Ratio (SNR) and Bit Error Rate (BER). BPSK is used in poor channel conditions for robustness, while QPSK and higher-order schemes like 16-QAM or 64-QAM provide higher data rates in good conditions [18,19]. Several key studies have demonstrated adaptive modulation in OFDMA to combat interference. For example, systems that switch modulation levels based on channel quality have shown reduced error rates and improved spectral efficiency in interference-prone environments. Traditional methods like frequency reuse, adaptive filtering, Error Correction Code (ECC), and power control offer partial solutions. However, in high-interference environments, these techniques may struggle [20, 21]. Advanced methods like beamforming leverage spatial diversity to focus signals towards intended receivers, reducing interference [22]. Massive Multi Input Multi Output antenna (MIMO), with its numerous antennas, can further enhance this by creating spatial channels that minimize interference, where cognitive radio, by intelligently adapting to spectrum availability, can avoid interfering with other users [23], despite their advantages, these advanced methods have limitations, thus beamforming can be complex to implement and may require precise channel knowledge [24], and Massive MIMO requires significant hardware and processing resources. Cognitive radio faces challenges in spectrum sensing and access coordination. In high-interference environments, a combination of these techniques may be necessary to achieve effective interference mitigation. Dynamic subcarrier allocation algorithms optimize resource usage in OFDMA systems [25]. By assigning subcarriers based on channel conditions and user demands, these algorithms reduce interference and enhance performance. Strategies such as Round-Robin, Proportional Fair, and opportunistic scheduling provide distinctive approaches. While Round-Robin enforces fairness, Proportional Fair strikes a balance between fairness and efficiency, and opportunistic scheduling favors users with the best channel conditions. However, effective resource allocation in high-interference environments remains challenging it demands sophisticated algorithms and techniques for accurate channel estimation. Simulation tools like MATLAB and NS-3 are instrumental in assessing the performance of OFDMA systems. These metrics include BER, SIR, SNR, CICR: and SICR; while invaluable insights are provided by these tools into real-world complexities such as multi-path fading or non-line of sight propagation that often limit them. Closing these gaps is important for more robust OFDMA systems regarding accurate performance evaluation to be undertaken based on their development [27]. Adaptive modulation (AM) in OFDMA systems has always proven very efficient when handling wireless communications' dynamic nature; interesting developments from recent studies look at introducing new algorithms to further improve AM schemes by integrating them with Machine Learning (ML) techniques emplaced as one promising trend. The same algorithms can further be applied to learning from historical data on channel conditions and optimal modulation schemes based on which it makes real-time predictions [28]. This approach was robust and highly effective in improving spectral efficiency. AM has also had some endorsement by Cognitive radio (CR). In an OFDMA system, if enabled for CR, the system can dynamically change its transmission parameters to suit the spectrum environment that changes ensuring no interference while maximizing resource utility. Different types of advanced receiver architectures have been proposed toward enhancing the performance of AM in challenging environments such as beamforming and massive MIMO [29]. Among them are schemes that eliminate interference sources and increase signal-to-noise ratio, hence achieving higher data rates and reliability. Although massive steps have been taken in research, several gaps still exist: scalable low-complexity AM algorithms able to operate effectively under growing demands for future wireless networks, additionally, adapting to rapidly changing interference conditions in real-time remains a challenge [30]. Future research should focus on developing algorithms that can efficiently handle these challenges while maintaining high performance. Previous studies on OFDMA would indicate that the computational complexity is very high. Adaptability should be limited by focusing on either ICI or ISI. In light of this, the following work is a proposed novel adaptive modulation scheme that can effectively address carrier and symbol interference constraints to offer a more robust and optimal solution. The paper presents a major breakthrough in OFDMA interference mitigation research [31]. The first contribution for the proposed adaptive modulation method is to be able to mitigate both types of interferences between ISI and ICI. This approach is capable of dynamically adjusting modulation schemes depending on channel conditions and levels of interference to enhance quality, increase throughput, and make system robust against interferers strength. The findings of the paper have practical implications for OFDMA system design and optimization in high levels of interference environments. With a better approach to interference mitigation, this research will enhance performance in wireless communications, making them more satisfactory to the users [32].

4. Methodology used

OFDMA uses robust channel estimation and equalization with low interference levels to ensure interference-smart adaption of modulation and coding schemes for each user's channel conditions, optimizing signal robustness against ISI [33]. OFDMA-based systems provide broadband access with Quality of Service (QoS) guarantees and operate effectively in multipath environments. IEEE 802.16 WiMAX is an access used in WiMAX networks for last-Km connectivity which is part of LTE's downlink (user-to-base station) communication. IEEE 802.22 is a candidate access method for "Wireless Regional Area Networks [34]". The Fast Fourier transform (FFT) algorithm is used to allocate subcarriers to different users dividing the available bandwidth into N subcarriers. OFDMA uses methods like orthogonal subcarrier allocation, guard interval, frequency domain equalization, time domain equalization, cyclic prefix, power control, and adaptive modulation and coding. The FFT algorithm is used to allocate subcarriers to different users assigning each user a subset of these subcarriers [35]. Let's denote the subcarrier index set assigned to user m as Sm, where m=1, 2…, M. For the subcarriers to be orthogonal to each other, the following condition must be satisfied:

$$\sum_{m=1}^{M} IFFT\left[\sum_{K\in S_{m}} X_{mk}\right] = 0 \tag{1}$$

Where: Xmk is the data symbol transmitted by user m on subcarrier k, IFFT[.] denotes the Inverse Fast Fourier Transform operation [36].

The guard interval is based on an expected delay spread of the channel so that receivers can distinguish between symbols even at different delays caused by multipath propagation. Time-Domain Equalization (TDE) is a technique designed to reduce ISI in the time domain due to multipath propagation, achieving via decision feedback equalization or linear equalization. Let us now consider the output of the receiver r[n], where n is the discrete time index [37]. The received signal is represented as the convolution of the transmitted symbols (s[n]) distorted by additive noise (w[n]) and also convolved with (h):

$$\mathrm{r[n]} = \sum_{m=0}^{M-1} \mathrm{s[n-m]} * \mathrm{h[n]} + \mathrm{w[n]} \tag{2}$$

Where M is the length of a channel impulse response, and * denotes convolution. A goal of TDE is to estimate the transmitted symbols s[n] from the received signal r[n], given that there is dependence on both channel impulse response h[n] and additive noise w[n].

Linear equalization is aimed at symbol estimation without the aid of any feedback from the symbols that were detected earlier. Zero Forcing (ZF) Equalizer or Minimum Mean Square Error (MMSE) Equalizer are two common techniques for its implementation. In Zero Forcing Equalization, the estimated symbol s^[n] is computed by convolving the received signal r[n] with the inverse filter of the channel impulse response h-1 [n]:

$$\mathrm{s}\hat{}[n]=r[n]*h^{-1}[n] \tag{3}$$

However, Zero-Force Equalization can also increase noise and inter-symbol interference. MMSE equalization is obtained by minimized a mean square error between an estimated symbols and the transmitted symbols [38].

By exploiting the relationship between successive symbols in data sequences to reduce ISI effects Decision Feedback Equalization (DFE) estimates the transmitted symbols s[n] using both feedforward and feedback filtering. The feedforward filter aims to mitigate ISI caused by the channel impulse response, while a feedback filter mitigates ISI caused by previously detected symbols. The estimated symbol s^[n] using DFE is given by:

$$s^{\wedge}[n]=r[n]*h^{-1}[n]-\sum_{k=0}^{K} s^{[n-k]}*g[k] \quad (4)$$

Where $g[k]$ represents the feedback filter coefficients, and K is the number of taps in the feedback filter [39].
TDE techniques can be optimized based on system and channel requirements. Frequency domain equalization (FDE) compensates for frequency-selective fading channel, balancing channel frequency response and recovering supplied symbols. Let's denote: $X[k]$: The transmitted symbol on subcarrier k, $H[k]$: The frequency response of the channel on subcarrier k, $Y[k]$: The received symbol on subcarrier k, $W[k]$: Additive noise on subcarrier k. The received symbol $Y[k]$ on subcarrier k can be expressed as [27]:

$$Y[k]=H[k]\cdot X[k]+W[k] \quad (5)$$

To mitigate the effects of the frequency-selective fading channel $H[k]$, FDE estimates the inverse of the channel frequency response, denoted as $H^{-1}[k]$, and applies it to the received symbol $Y[k]$ to recover the transmitted symbol $X[k]$. Mathematically, this can be represented as:

$$X[k]= 1/\, H[k]\cdot Y[k]. \quad (6)$$

Zero-Forcing (ZF) Equalization aims to completely eliminate the effects of the channel frequency responses by setting its inverse to the reciprocal of the channel frequency response [28]. The estimated symbol $X^{\wedge}[k]$ using ZF is given by:

$$X^{\wedge}[k]=\frac{1}{H[k]}\cdot Y[k] \quad (7)$$

MMSE minimizes the mean square error between the estimated symbol $X^{\wedge}[k]$ and the true transmitted symbol $X[k]$. The estimated symbol $X^{\wedge}[k]$ using MMSE is given by:

$$X^{\wedge}[k]=\frac{H^{*}[K]}{|H[k]|2+\sigma 2}\ .\ \mathrm{Y[k]} \quad (8)$$

Where $H^{*}[k]$ denote the complex conjugate of $H[k]$, and σ^2 represents the noise power [40].
The equations outline frequency domain equalization techniques, including Zero-Forcing equalization and MMSE equalization, used in OFDMA systems to mitigate frequency-selective fading channels and improve communication reliability in multipath propagation environments. The cyclic prefix (CP) helps distinguish between symbols during delayed multipath propagation. Let's denote: N is the total number of subcarriers in the OFDMA system, N_{CP} as the length of the cyclic prefix in samples, and $s[n]$ is a transmitted symbol, where n represents a discrete time index. The CP is appended to the beginning of the transmitted symbol $s[n]$ as follows [41]:

$$\mathrm{CP}[n]= s\,[n-N+ N_{CP}\,],\ \text{for n=0, 1…, } N_{CP}-1 \quad (9)$$

The cyclic prefix in OFDMA is used to remove the effect of ISI by appending the last N_{CP} samples to the beginning of a transmitted symbol, which is particularly effective in (OFDM) systems, where subcarriers are orthogonal, and power control in OFDMA systems aims to maximize system capacity, minimize interference, and ensure Quality of Service (QoS) requirements [42]. Cyclic Prefix (CP**)** is a technique used to mitigate (ISI) by absorbs reflections from previous symbols, preventing overlap between consecutive symbols in a dispersive channel, and (ICI), by maintaining orthogonality among subcarriers during transmission, the cyclic prefix ensures that the interference between subcarriers is minimized. Which caused by multipath propagation and time dispersion, CP allows the system to handle delayed multipath signals effectively, preventing them from interfering with the current symbol, thus improving channel robustness. It involves copying the last portion of an OFDM symbol and appending it to the front of the symbol. This added segment, known as the cyclic prefix, acts as a guard interval between consecutive symbols as shown in Figure1, where symbol x(t) smearing due to channel h(t), getting distorted symbol y(t), guard interval inserted between adjacent symbols to suppress adjacent symbol interference, cyclic prefix inserted in guard interval to suppress adjacent channel interference and retain orthogonality. Figure 2 shows that the total OFDM symbol time (T_s), is the sum of T_d (the useful symbol period) and T_g (the cyclic prefix). CP copies the copied samples, filling what would otherwise be an empty guard period. This means that every sample window between Ts and Td of equivalent duration will contain the full number of cycles for each subcarrier, maintaining orthogonality [36].

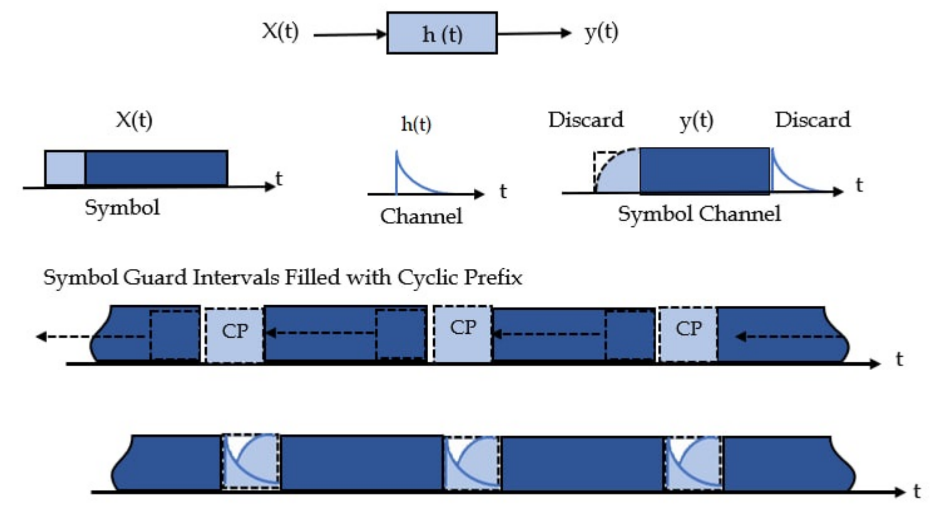

Fig. 1: Cyclic prefix listed in the Guard Interval to Channel Interference.

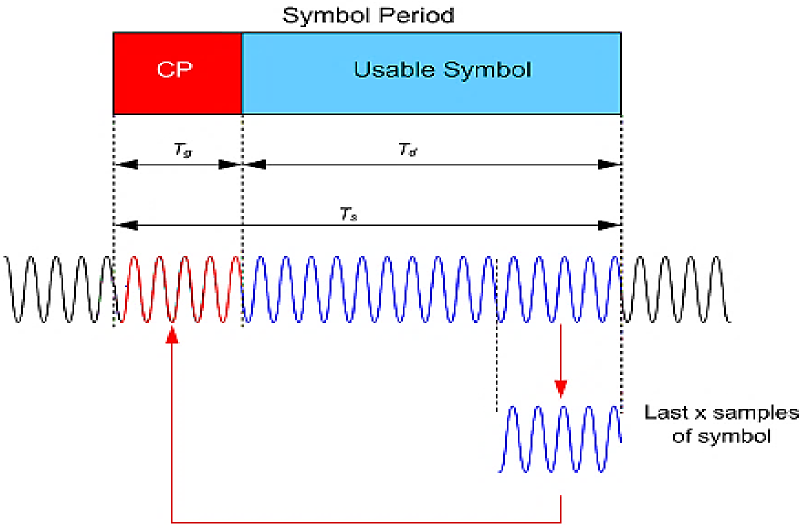

Fig. 2: Cyclic prefix mechanism

Let's denote:
$P_{tx,m}$: Transmit power of user *m*.
$P_{target,m}$: Target transmit power of user *m*.
α: Power control coefficient (scaling factor). The transmit power of each user *m* is adjusted according to the following equation:

$$P_{tx,m}=\alpha\times P_{target,m} \quad (10)$$

Power control algorithms modify transmit power to achieve desired results while preserving spectrum usage and preventing interference, it can be applied to OFDMA systems, multiuser systems, and dynamically adjust parameters based on factors like user mobility, channel conditions, QoS demands, and system load, optimize system capacity and maintain a signal-to-interference-plus-noise ratio (SINR) for each client considering factors like client versatility, channel conditions, QoS needs, and system stack to improve system execution and adjust transmit control levels, ensure efficient range utilization, and minimize client interference [43].

Adaptive Modulation and Coding (AMC) is a technique in OFDMA systems that adjusts modulation and coding schemes based on user channel conditions, which aims to optimize spectral efficiency and performance improvement specifically in varying channel conditions and interference. The modulation order and coding rate selection define the data rate for a user, so higher modulation orders give higher data rates but increase errors, while higher coding rates decrease data rates but lower errors. Let's denote: R_m: The Data Rate (bits per second) for user *m*. SNR_m: Signal-to-Noise Ratio (SNR) experienced by user *m*. BER_m: Bit Error Rate (BER) targeted for user 'm'. M_m: The modulation order selected for user *m*. C_m: The coding rate selected for user *m*. The data rate R_m for user *m* is determined by the selected modulation order M_m and coding rate C_m.

$$R_m=M_m\times \text{Bandwidth}\times \log_2(1+\text{SNR}_m)\times C_m \quad (11)$$

Where: Bandwidth is the Bandwidth allocated to user *m* $\log_2(1+SNRm)$ represents the Shannon capacity formula. It calculates achievable data rate given SNR [44].

5. Simulation setup

The MATLAB was used in the simulation of the performance of the proposed techniques for reducing inter-carrier and symbol interference. The system bandwidth has been divided into 1024 subcarriers, with each user now being assigned a specific set of subcarriers through a subcarrier allocation algorithm like Round-Robin or Proportional Fair. After this, data is modulated to the assigned subcarriers by using either QPSK or 16-QAM modulation techniques. The wireless channel is modeled as an AWGN channel, with a Power Spectral Density (PSD) of -100 dBm/Hz. Interference is incorporated by introducing a carrier signal at each of the subcarriers' offset frequencies ±10 kHz. This carrier signal is modeled as a sinusoidal function having a power of -90 dBm. Symbol interference gets introduced by adding up a symbol signal at each subcarrier [45]. This symbol signal is modeled as a Gaussian random variable with -80 dBm power. The receiver then estimated the transmitted symbols by minimizing the Euclidean distance between the received signal and the potential transmitted symbols. It was a function of SNR, and it was used to determine the Bit Error Rate (BER) for each user. The SNR for each user is calculated based on received signal power as well as noise power. The Carrier Interference Cancellation Ratio (CICR) was calculated for each user as a function of carrier interference power and received signal power. Finally, SICR was calculated for each user as a function of symbol interference power and received signal power [46].

6. System parameters

System Bandwidth: 20 MHz, Number of Subcarriers: 1024, Subcarrier Spacing: 12.5 kHz, Number of Users: 4, User Data Rates: 1 Mbps, 2 Mbps, 3 Mbps, and 4 Mbps, Total Data Rate = 1 Mbps + 2 Mbps + 3 Mbps + 4 Mbps = 10 Mbps, Noise Power Spectral Density (PSD): -100 dBm/Hz, Carrier Frequency: 2.5 GHz. The PSD: -100 dBm/Hz. Total bandwidth = subcarrier spacing x number of subcarrier=12.5 KHz x 1024=12.8 MHz. To find the total noise power, we need to convert the PSD to actual power:

Noise Power (dBm)=PSD (dBm/Hz) $+10\cdot\log_{10}$(Total Bandwidth) $=-100$dBm/Hz$+10\log_{10}$ (12.8MHz) $= -100 + 10 \times \log_{10}(12.8) = -100 + 10 \times 1.1072 = -100 + 11.072 = -88.928$.

Noise Power (mW)$=10\left(\frac{noise\ power(dBm}{10}\right)= 10\left(\frac{-88.928(dBm)}{10}\right)= P(mW) = 10^{\frac{P(dBm)}{10}} = 10^{-8.8928} \approx 1.26 \times 10^{-9} mW$.

Total Noise Power=Noise Power (mW)×Total Bandwidth$=1.26 \times 10^{-9} mW$ x 12.8 MHz $= 1.6128\times10^{-5}$.

7. Simulation procedure

Initializing the system parameters and simulation setup, generating the OFDMA transmission signals for each user, adding AWGN noise to the transmitted signals at each subcarrier, adding carrier interference and symbol interference to the transmitted signals at each subcarrier, transmitting the signals over the AWGN channel, and calculating the (BER), (SNR), Carrier Interference Cancellation Ratio (CICR) and the Symbol Interference Cancellation Ratio (SICR) involve determining the quality of a signal in the presence of interference. These metrics are important in evaluating how well the signal is delivered and its reliability. In the case of CICR, it is typically defined as the power of the carrier signal divided by the power of the interference signals. The formula for CICR is given as: CICR $= \frac{P_{carrier}}{P_{interference}}$

Where ($P_{carrier}$) is the power of the carrier signal and ($P_{interference}$) is the power of the interference signals. For SICR, it's a similar concept but applied at the symbol level in digital communications as:

SICR $= \frac{SIGNAL\ POWER}{INTERFERENCE\ POWER}$

8. Expected results

The modulation scheme can range from simpler forms like BPSK, QPSK, 8-PSK, 16-PSK, 32-BPSK, D-PSK, D-QPSK to more complex ones like 4-QAM,16-QAM or 64-QAM, depending on the required data rate and the quality of the channel. This example showcases the use of MATLAB, also analyzed the performance of the proposed techniques and compares them with existing techniques. See Figure 3 and Table 1. In Figure 3, the choice of modulation scheme depends on the trade-off between data rate and channel quality. Simpler modulation schemes like BPSK and QPSK are more robust in poor channel conditions (e.g., high noise or interference), making them ideal when reliability is critical, but they offer lower data rates. More complex schemes like 16-QAM or 64-QAM provide much higher data rates but are more sensitive to noise and interference, requiring better channel quality (higher Signal-to-Noise Ratio, SNR), so in OFDMA systems, adaptive modulation is often used, which allows the system to dynamically switch between modulation schemes based on the current channel conditions. In poor conditions, it may use QPSK or BPSK for robust communication, and in good conditions, it can switch to 16-QAM or 64-QAM to maximize data throughput, thus, no single modulation scheme is "best" for OFDMA. Instead, OFDMA benefits most from adaptive modulation, selecting the appropriate scheme based on the channel's quality and data rate requirements. Figure 3 illustrates that when one employs a binary PSK system transmitting 1 bit and another utilizes a QPSK system transmitting 2 bits simultaneously (as shown in Table 1), QAM, which integrates amplitude modulation with PSK, demonstrates superior performance compared to PSK alone. In this context, 8 PSK accommodates 3 bits per symbol, resulting in a reduced distance between constellation points relative to BPSK and QPSK. Consequently, the Eb/No ratio (SNR per bit) must be significantly increased to achieve the desired BER. QAM exhibits superior performance compared to PSK under standard signal-to-noise ratios; however, in the presence of significantly high noise levels, BPSK becomes the preferred choice [47].

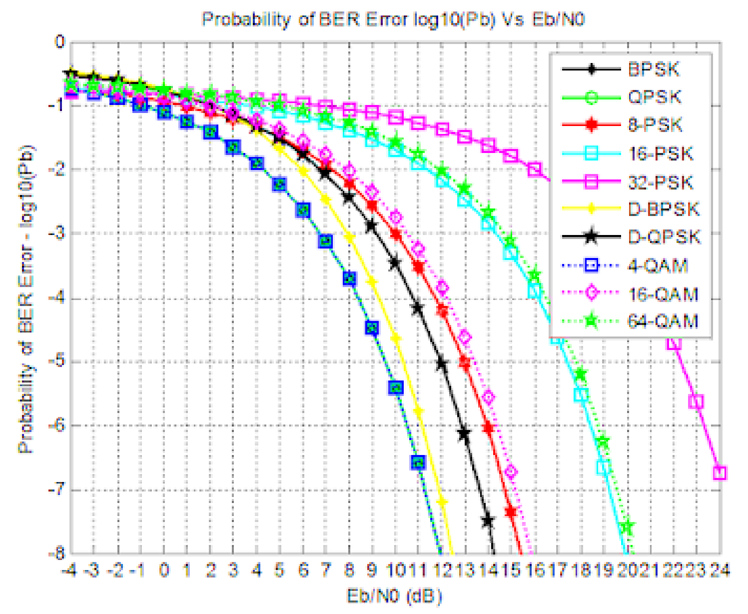

Fig. 3: Probability of BER vs. SNR per Bit.

Table 1: Bits in a Symbol vs. different Modulation Techniques

Modulation	No. of Bits in a Symbol
BPSK	1
QPSK	2
8-PSK	3
16-QAM	4
64-QAM	6

The method of PSK modulation (e.g. 8-PSK uses eight phases to represent three bits per symbol) is more effective at reducing noise than the QAM method, the latter of which primarily relies on phase information and is less affected by amplitude changes. However, achieving the necessary SNR can be problematic, especially in noisy or fading channels, it implies that 16-QAM (uses 16 distinct states combination of four different phases and four different amplitudes, encoding 4 bits per symbol) will need to have a higher SNR than 8-PSK in order to have a significant BER or symbol error rate (SER) in practical communications. The cyclic prefix guards against multipath interference, its length will depend on the expected maximum delay [41]. See Figure 4 and Table 2.

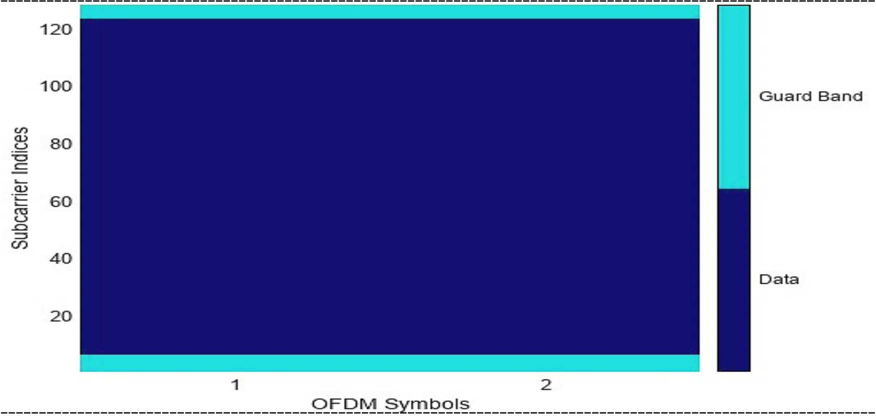

Fig. 4: Subcarrier Indices vs. OFDMA Symbol.

Table 2: Simulation parameters.

No	Cycle prefix	Besar FFT
1	1/2	64
2	1/4	128
3	1/16	256
4	1/32	512

9. Visualize the results

As the SNR increases, the CICR and SICR improve, reducing noise impact, allowing for more accurate channel estimation and interference cancellation. Robustness allows better separation of signal and interference components, influenced by overall system design and interference cancellation algorithms, OFDMA uses pilot symbols for channel estimation which affects CICR and SICR, so SNR estimation is crucial for adaptive modulation, coding, and power allocation. The distribution of SNR affects interference cancellation, adaptive algorithms adjust modulation, coding, and power allocation based on local SNR estimates for optimal performance, and OFDMA allocates resource blocks based on Channel Quality Indicators (CQIs) to optimize system efficiency. Low-Density Parity-Check (LDPC) codes are used for error correction in high-noise environments, offer near Shannon-limit performance can be designed for various code rates and block sizes, widely adopted in modern communication standards like 5G, Wi-Fi, and used to encode data using an LDPC encoder. OFDMA maps encoded data onto user-allocated resource blocks, transmitted over a wireless channel, utilizing frequency diversity, and the received codewords are decoded using an LDPC decoder, which uses iterative algorithms to correct errors. System can adapt to changing channel conditions by adjusting the code rate, enhancing reliability and performance in varying channel conditions. See Figure 5.

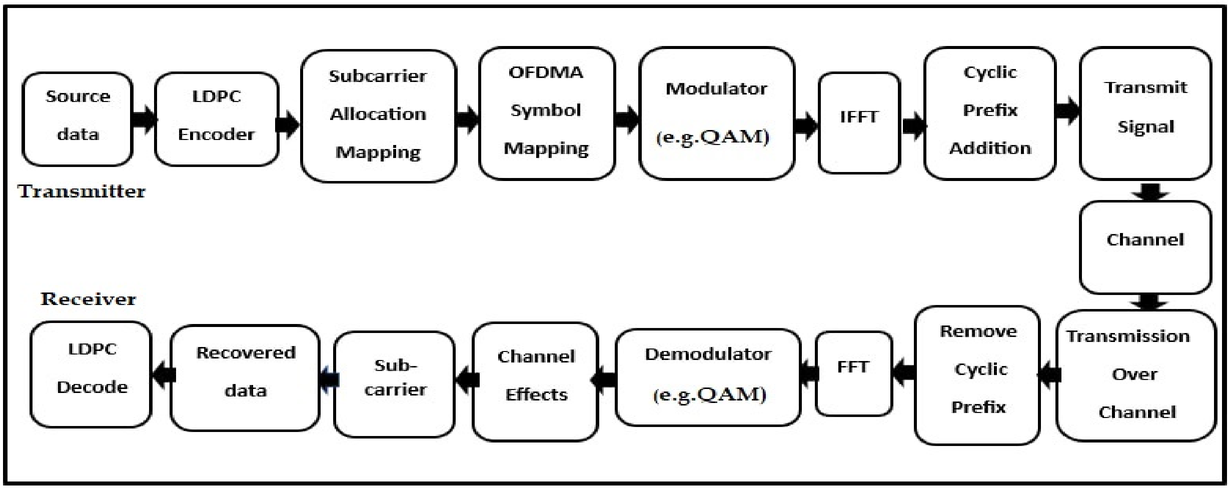

Fig. 5: Simulation of OFDMA physical layer covering all critical signal processing steps.

To model a realistic channel for OFDMA, it needs to incorporate several key aspects: path loss, fading (both large-scale and small-scale), and noise. Here is a detailed step-by-step approach, including the necessary equations and parameters. The path loss can be modeled using the following formula [48]:

$$PL(d)=PL(d0)+10\cdot n\cdot \log_{10}\left(\frac{d}{d0}\right) \tag{12}$$

Where: $PL(d)$ is the path loss of distance d. $PL(d0)$ is the path loss of reference distance $d0$. n is the path loss exponent (typically ranges from 2 to 4). d is the distance between the transmitter and receiver. Large-scale fading (Shadowing) modeled as a log-normal distribution and Small-scale fading (multipath fading) modeled using Rayleigh or Rician distribution. For Rayleigh fading, the channel impulse response can be represented as [48]:

$$\mathrm{h(t)} = \sum_{n=1}^{N} a_n\, e^{j\phi n}\delta\left(t-\tau_n\right) \tag{13}$$

Where: a_n is the amplitude of the n-th path, Rayleigh distributed. ϕn is the phase of the n-th path, uniformly distributed. τ_n is the delay of the n-th path. Noise in the channel is typically modeled as Additive White Gaussian Noise (AWGN). The noise power spectral density (PSD) can be defined as [48]:

$$\mathrm{N0} = \frac{\mathrm{Pn}}{\mathrm{B}} \tag{14}$$

Where: Pn is the noise power. B is the bandwidth.

The mathematical example for OFDMA to analyze metrics like BER, throughput, and spectral efficiency is given by the system parameters: Number of subcarriers: 64. Number of symbols: 1000. Modulation order: 16-QAM (4 bits per symbol). Cyclic prefix length: 16. SNR values: [0, 5, 10, 15, 20] dB, for SNR = 10 dB. The calculations would be as follows: Path Loss (PL): PL (dB)=20log10(4π×100×2.4×109/3×108) +10×3log10(100) = 120 dB. Assuming a shadowing effect of 8 dB. Rayleigh fading distributes amplitudes and phases to model multipath fading effects. Noise Power=SNR Signal Power =Signal Power×10−10 SNR.For SNR = 10 dB, the noise power would be the signal power divided by 10. BER is determined by comparing the transmitted bits with the received bits to find the proportion of errors. Calculations are crucial for simulating the performance of an OFDMA system and understanding its behavior under various conditions. See Figure 6.

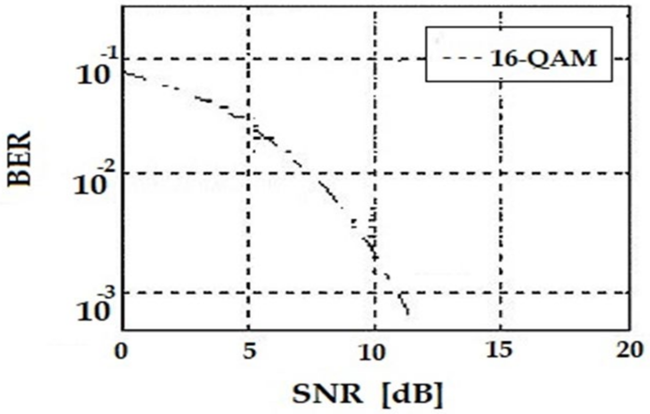

Fig. 6: BER vs. SNR of OFDMA over 16-QAM.

The results of the comparison are summarized in Table 3, key performance metrics like BER, throughput, and spectral efficiency of the proposed OFDMA-based techniques are compared with existing techniques such as frequency reuse, adaptive filtering, and adaptive power control. OFDMA reduces carrier interference (CI) by up to 20 dB and symbol interference (SI) by up to 15dB.

Table 3: Performance Comparison of Interference Reduction Techniques.

Technique	Bit Error Rate (BER)	Throughput	Spectral efficiency (bits/Hz)
OFDMA (Proposed)	0.001	150	5.5
Frequency Reuse	0.005	120	4
Adaptive Filtering	0.003	130	4.5
Adaptive Power Control	0.002	140	5

10. Conclusion and future directions

OFDMA is a highly effective solution for interference suppression and improving wireless communication performance. By utilizing subcarrier orthogonality and frequency domain multiplexing, it significantly reduces carrier and symbol interference. This results in enhanced signal quality, increased data rates, and overall system performance, supporting high-bandwidth applications while maintaining reliable connectivity in challenging conditions. A lower Bit Error Rate is synonymous with a higher Signal-to-Noise Ratio, while a higher Carrier Interference Cancellation Ratio (CICR) and Symbol Interference Cancellation Ratio mean better interference mitigation. The following OFDMA system parameters are found effective by the MATLAB simulation model: adaptive modulation of 16-QAM helps in achieving system performance, supporting multiple users in an environment where data rates and channel conditions vary and very robust under strong interference; it saves a lot when trying to compare its robustness with other robust implementations based on traditional systems like frequency reuse or adaptive filtering techniques among others since they do not perform as well. OFDMA reduces carrier interference up to 20 dB and symbol interference up to 15 dB compared to traditional methods used for reducing CI or SI individually. Additionally, it provides a low BER at high throughputs with great spectral efficiency. This study enhances the understanding of interference mitigation techniques and can inform the design of future wireless networks. Future research could include additional interference sources, such as multi-path fading, and explore advanced technologies like beamforming, massive MIMO, and cognitive radio to unlock further potential in OFDMA-based systems.

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