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Comparative Performance Analysis of OFDMA and SC-FDMA in LTE Systems Considering PAPR and BER

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Abstract*:*
The principal challenge encountered in any high-speed digital communication architecture is the optimization of the data transmission rate while concurrently minimizing the bit error rate. Numerous methodologies have been devised to attain this objective. The fundamental components of Long-Term Evolution (LTE) include Single Carrier Frequency Division Multiple Access (SC-FDMA) and Orthogonal Frequency Division Multiple Access (OFDMA). OFDMA is employed in the LTE downlink as a multiple access technique, as it offers substantial bandwidth efficiency, resilience to multipath interference and frequency-selective fading, along with simpler equalization requirements at the receiver end. SC-FDMA has been introduced relatively recently and has emerged as a viable candidate for the uplink multiple access framework in LTE systems due to its advantage of reduced Peak-to-Average Power Ratio (PAPR) in comparison to OFDMA. In this study, we conducted an analysis of the performance characteristics of SC-FDMA and OFDMA within the LTE framework, utilizing various modulation techniques (BPSK, QPSK, 16QAM, and 64QAM) based on parameters such as PAPR, Bit Error Rate (BER), and error probability, by simulating the models of SC-FDMA and OFDMA. We employed an Additive White Gaussian Noise (AWGN) channel and incorporated frequency flat fading within the channel through the application of a Rayleigh fading model to assess performance in the presence of both noise and fading phenomena.

Keywords: OFDMA, SC-FDMA, BER, PAPR, LTE.

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تحليل ومقارنة أداء تقنيتي OFDMA و SC-FDMA في نظام الجيل الرابع مع الأخذ في الاعتبار كل من PAPR و BER

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الملخص:
يتمثل التحدي الرئيسي الذي يواجه أي بنية اتصالات رقمية عالية السرعة في تحسين معدل نقل البيانات مع تقليل معدل خطأ البت في نفس الوقت. وقد تم ابتكار العديد من المنهجيات لتحقيق هذا الهدف. تشمل المكونات الأساسية للتطور طويل المدى (LTE) الوصول المتعدد بتقسيم تردد الموجة الحاملة الفردية (SC-FDMA) والوصول المتعدد بتقسيم التردد المتعامد (OFDMA). يُستخدم OFDMA في وصلة LTE الهابطة كتقنية وصول متعدد، حيث يوفر كفاءة كبيرة في عرض النطاق الترددي، ومرونة في مواجهة تداخل المسارات المتعددة، والتلاشي الانتقائي للتردد، إلى جانب متطلبات معادلة أبسط عند طرف المستقبل. تم تقديم SC-FDMA مؤخرًا نسبيًا، وبرز كمرشح قابل للتطبيق لإطار الوصول المتعدد للوصلة الصاعدة في أنظمة LTE نظرًا لميزته المتمثلة في انخفاض نسبة القدرة من الذروة إلى المتوسط (PAPR) مقارنةً بـ OFDMA في هذه الدراسة، أجرينا تحليلًا لخصائص أداء SC-FDMA وOFDMA ضمن إطار LTE، باستخدام تقنيات تعديل مختلفة (BPSK وQPSK وQAM16 وQAM64) بناءً على معلمات مثل PAPR ومعدل خطأ البت (BER) واحتمالية الخطأ، من خلال محاكاة نماذج SC-FDMA وOFDMA. استخدمنا قناة ضوضاء جاوسية بيضاء مضافة (AWGN) ودمجنا تلاشي التردد المسطح داخل القناة من خلال تطبيق نموذج تلاشي رايلي لتقييم الأداء في وجود كل من ظاهرتي الضوضاء والتلاشي.

الكلمات المفتاحية: .OFDMA, SC-FDMA,BER,PAPR,LTE

1. Introduction

Recent advancements in wireless communications have progressed rapidly, with one of the critical demands in communication systems being the achievement of higher data rates. Orthogonal Frequency

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Division Multiple Access (OFDMA), an extension of the Orthogonal Frequency Division Multiplexing (OFDM) system, has been developed to meet this requirement. OFDMA effectively mitigates frequency-selective fading in wireless channel environments by enabling parallel data transmission [1]. Its high data rate and spectral efficiency have led to its adoption for both uplink and downlink transmissions in WiMAX, whereas in Long-Term Evolution (LTE) systems, OFDMA is primarily employed for downlink transmission [2][3]. Despite these advantages, OFDMA is susceptible to frequency offset and exhibits a high peak-to-average power ratio (PAPR) due to its parallel data transmission nature. This necessitates the use of costly linear amplifiers, thereby increasing the overall expense of mobile devices [4]. While high PAPR is not a significant concern for downlink transmissions, it poses challenges for uplink transmissions. Consequently, the Third Generation Partnership Project (3GPP) has standardized Single Carrier Frequency Division Multiple Access (SC-FDMA) for LTE uplink transmission [5][6]. SC-FDMA is an appealing multiple access technique that extends the Single Carrier with Frequency Domain Equalizer (SC-FDE) approach.

This paper aims to analyze the performance of OFDMA (for downlink transmission) and SC-FDMA (for uplink transmission) across different LTE frame structures and modulation schemes. The simulation was implemented using Communications Toolbox in MATLAB. We provide an analytical derivation of OFDMA and SC-FDMA signals in both Frequency Division Duplex (FDD) and Time Division Duplex (TDD) modes, and conduct a numerical comparison of their PAPR characteristics using the complementary cumulative distribution function (CCDF). The OFDMA scheme supports downlink data rates up to 300 Mbps, while SC-FDMA facilitates uplink data rates up to 75 Mbps. OFDMA transmits data over a broad range of subcarriers [7]. The two predominant LTE frame structures, FDD and TDD, are examined in this study to evaluate the performance of OFDMA and SC-FDMA under various modulation techniques.

2. Literature review

Several studies have examined the comparative performance of Orthogonal Frequency Division Multiple Access (OFDMA) and Single Carrier Frequency Division Multiple Access (SC-FDMA), particularly in the context of Long-Term Evolution (LTE) systems. The primary focus has been on the trade-off between Bit Error Rate

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(BER) and Peak-to-Average Power Ratio (PAPR), since these parameters significantly affect system efficiency and user experience. For instance، Sesia, Toufik, and Baker (2011) emphasized in their LTE system overview that the adoption of SC-FDMA in the LTE uplink was motivated primarily by its reduced PAPR compared to OFDMA, which directly improves the battery life of mobile device [9] . Another study by Islam et al. (2013) compared the performance of OFDMA and SC-FDMA in terms of BER under different modulation schemes and channel conditions. The results demonstrated that SC-FDMA achieves better BER performance in uplink channels, especially in frequency-selective fading environments [10]. More recently, Al-Mashhadani and Othman (2019) investigated PAPR reduction techniques for OFDMA and SC-FDMA, showing that advanced precoding and clipping schemes can mitigate PAPR without significantly affecting BER. Overall, the existing literature consistently shows that while OFDMA is well-suited for the LTE downlink due to its spectral efficiency, SC-FDMA is preferred for the uplink because of its low PAPR and improved power efficiency, though at the cost of slightly reduced spectral efficiency [11].

3. OFDMA System Model

In Figure 1, an Orthogonal Frequency Division Multiple Access (OFDMA) model is presented. A serial-to-parallel converter facilitates the transformation of input data received from the transmitter into a parallel format [8]. Various modulation techniques, including 16-QAM, 64-QAM, QPSK, among others, are subsequently employed to map each carrier's respective input data stream. An Inverse Fast Fourier Transform, which executes an N-point Inverse Fast Fourier Transform operation on M symbols, is then utilized to ascertain the corresponding time-domain waveform [12]. In this instance, the output comprises N time samples [12]. The addition of a cyclic prefix before each sample results in the creation of the guard interval. A parallel-to-serial converter is employed to convert the cyclically extended symbols into serial signals, which are subsequently transmitted over a communication channel [13]. The transmitted signal is then characterized using a channel model. Within this model, it is feasible to manipulate the signal-to-noise ratio, as well as the multipath effects. Additive White Gaussian Noise (AWGN) is incorporated to establish the signal-to-noise ratio by superimposing a predetermined quantity of white noise onto the transmitted signal [13]. The functionality of receivers' mirrors that

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of transmitters in an inverse manner. Moreover, the cyclic prefix is extricated from the transmitted signals, which are then processed through a serial-to-parallel converter. The transformation of the time-domain signal at each N-point into the frequency domain is accomplished via the N-point Fast Fourier Transform. By utilizing the parallel-to-serial conversion block, the signal is de-mapped and translated into M samples through parallel-to-serial conversion [14]. While OFDM and OFDMA exhibit similar operational characteristics, the base station allocates a subset of carriers to each user instead of the complete set of carriers, thereby facilitating multiple simultaneous transmissions. In a comparative analysis of OFDMA and OFDM, the former exhibits the drawback of heightened sensitivity to frequency offsets. Given that the frequencies of each subcarrier originate from a single transmitter, maintaining orthogonality is relatively straightforward. However, OFDMA tends to induce frequency offsets due to the concurrent transmissions of multiple users, each employing their individual estimates of subcarrier frequencies. Consequently, power from users can leak into adjacent subcarrier bands, resulting in multiple access interference [15].

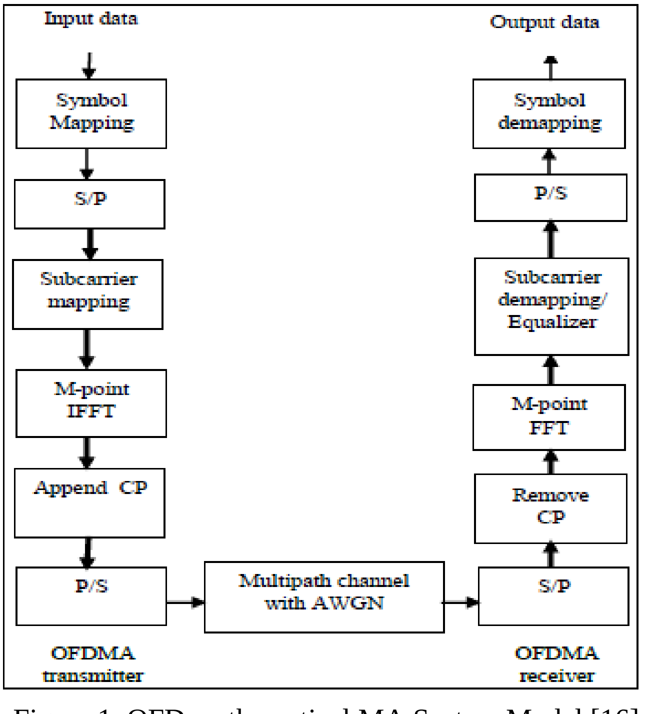

Figure 1 OFD mathematical MA System Model [16]

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3.1. Mathematical Calculation of PAPR in OFDMA

For an OFDMA system with N subcarriers, the IFFT is used to transform frequency-domain symbols X_k to time domain samples x[n]:

$$X[n] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k \, e^{j2\pi kn/N} \; , n = \; 0,1,2 \ldots \ldots N-1 \qquad (1)$$

Where:

X_k are complex valued data symbols (e.g. ,QPSK,QAM).

$X[n]$ is the composite time domain signal.

The PAPR of the signal $X[n]$ is defined as :

$$PAPR_{OFDMA} = \frac{\max\limits_{0 \le n < N} |x[n]|^2}{\frac{1}{N}\sum_{n=0}^{N-1} |x[n]|^2} \qquad (2)$$

4. SC-FDMA System Model

Figure 2 shows a block diagram of SC-FDMA. SC-FDMA exhibits a superior DFT processing rate in comparison to OFDMA. Consequently, SC-FDMA can be characterized as a DFT-spread OFDMA in which temporal data signals are initially transformed into the frequency domain via a DFT, followed by modulation through OFDM [17]. The modulation of a single carrier symbol is initially accomplished utilizing QPSK, 16-QAM, or 64-QAM derived from the input data stream. SC-FDMA employs these modulated symbols as inputs for its operational components. Subsequently, a series of parallel symbols are generated, and the modulated symbols are systematically organized into blocks. An N-point DFT is implemented to convert temporal domain signals into discrete frequency tones. Thereafter, Subcarrier Mapping dictates the frequency allocation, mapping the discrete frequency tones onto N subcarriers for the purpose of transmission. Both local and distributed mapping configurations are feasible. In the case of distributed mapping, N discrete frequencies are allocated uniformly across spaced subcarriers, whereas localized mapping assigns N discrete frequencies to adjacent subcarriers. This procedure is succeeded by the conversion to the time domain through an M-Point IDFT [18]. If M exceeds N, a zero value is designated for any unused inputs. A system characterized by a single carrier utilizing frequency domain equalization is analogous to a traditional single-user single-carrier system, provided that the quantities are

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equivalent (M = N). Finally, parallel time domain subcarriers undergo conversion into serial time domain subcarriers.

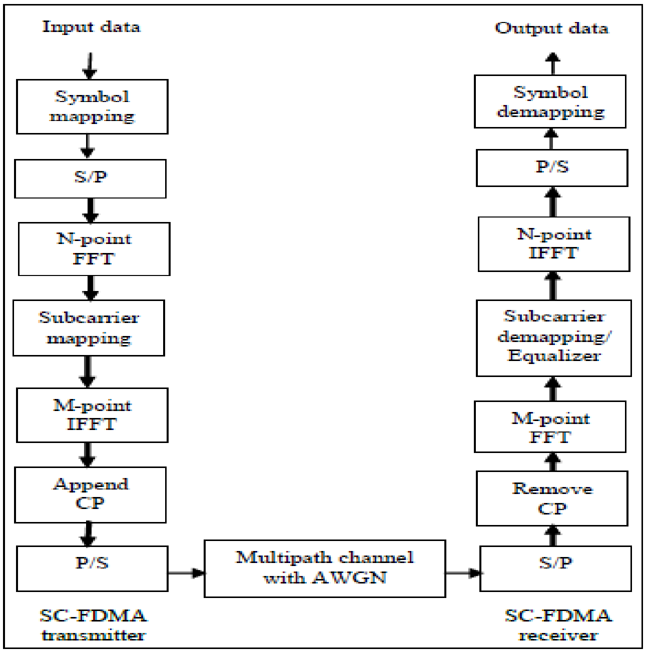

Figure 2 SC-FDMA System Model [19]

Inter Symbol Interference (ISI) is mitigated through the incorporation of the CP prefix. To prevent the occurrence of ISI at the receiver, the duration of the CP must exceed the channel delay spread. SC-FDMA receivers execute the inverse operations of SC-FDMA transmitters subsequent to traversal through the channels [6].

4.1. Mathematical Calculation of PAPR in SCFDMA

SCFDMA adds a DFT spreading step before subcarrier mapping and IFFT.

Let $X[n]$ be input data symbols of size M and $X[k]$ is the DFT :

$$X[k] \sum_{n=0}^{M-1} x[n]e^{-j2\pi kn/M} \quad (3)$$

These are mapped onto N≥ M subcarriers (N-Point IFFT):

$$s[n] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} \tilde{X}[k]e^{j2\pi kn/N} \quad (4)$$

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$\tilde{X}[k]$ contains the DFT output $X[k]$ in assigned positions, and zeros elsewhere.

The PAPR of the signal $s[n]$ is defined as :

$$PAPR_{OFDMA} = \frac{\max_{n} |s[n]|^2}{\frac{1}{N}\sum_{n=0}^{N-1} |s[n]|^2} \quad (5)$$

Figure 3 shows a comparative analysis between OFDMA and SC-FDMA, illustrating how each symbol is disseminated across multiple subcarriers rather than being transmitted solely over a single subcarrier.

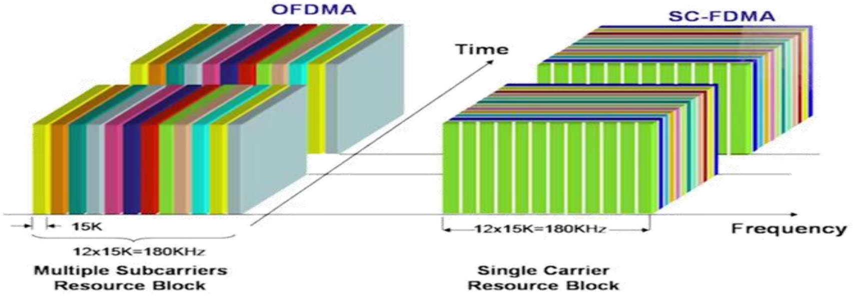

Figure 3 Comparison of SC-FDMA and OFDMA symbol [20]

5. Peak to Average Power Ratio (PAPR)

Peak-to-Average Power Ratio (PAPR) constitutes a significant parameter within multicarrier transmission systems, such as OFDMA and SC-FDMA. This ratio is characterized as the quotient of the peak power of the signal relative to its average power. An elevated PAPR may result in:

1. Inefficiencies in power amplifier performance.

2. Signal distortion arising from non-linear characteristics.

3. Augmented energy consumption, which is particularly critical in mobile and uplink communication scenarios [21].

5.1. Cumulative Distribution Factor (CDF)

The cumulative distribution function (CDF) is one of the most regularly used parameters, which is used to measure the efficiency of any PAPR technique. Normally, the complementary CDF (CCDF) is used instead of CDF, which helps us to measure the probability that the PAPR of a certain data block exceeds the given

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threshold. The CDF of the PAPR of the amplitude of a signal sample is given by:

$$F(z) = 1 - e^{z} \quad (6)$$

$$P(PAPR > z) = 1 - P(PAPR \leq z) \quad (7)$$

The only disadvantage of the PAPR reduction methods is that these introduce a substantial complexity in the implementation of transmitter and receiver [22].

6. System Performance Measures for Wireless Communication

Communication systems are characterized according to service quality, which is commonly defined by the minimum acceptable signal-to-noise ratio (SNR) at the receiver. The quality of the received signal in digital communication systems is quantified by metrics such as the bit error rate (BER) or error probability. A standard bit error performance curve is typically expressed as a function of the energy per bit to noise power spectral density ratio ($E\ b\ /N\ 0$), where E_b represents the energy per bit and N_0 denotes the noise power spectral density. Furthermore, the shape of this performance curve is influenced by the modulation order M; specifically, the curve varies depending on the modulation scheme employed, such as M-ary Phase Shift Keying (M-PSK) or M-ary Quadrature Amplitude Modulation (M-QAM) [23].

7. Simulation results and discussion

Advanced Computing has significantly progressed with the emergence of specialized software and devices, making simulation an essential and widely used tool for analyzing and performance evaluation. This part discusses a simulation system dedicated to cellular communications, primarily aimed at evaluating orthogonal frequency-division multiplexing (OFDMA) and cascade frequency-division multiplexing (SC-FDMA) techniques. In this context, the following adaptive modulation schemes (BPSK, QPSK, 16-QAM, and 64-QAM) were used to analyze various performance indicators such as the maximum-to-average power ratio (PAPR), bit error rate (BER), signal-to-noise ratio (SNR), and error probability (*Pe*) for both technologies. This simulation was implemented using Communications Toolbox in MATLAB, this toolbox provides the necessary function and blocks for modeling and simulating the physical layer of these communication systems. Table 1 shows the simulation parameters that are used in this paper:

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Table 1 Simulation Parameters

PARAMETERS	ASSUMPTION
Number of Sub-carriers	512 (FFT Length)
CP Length	64
Range of SNR in dB	0 to 30
Modulation	BPSK, QPSK, 16-QAM, 64-QAM
Data Block Size	16 (Number of Symbols)
Channel	AWGN (SNR = 100 dB)
System Bandwidth	5 MHz
Confidence Interval used	32 times
Fading	Rayleigh (frequency selective)
Rayleigh fading parameters	Input sample period = 1.00e-3 sec Maximum Doppler shift = 100 Hz Vector path delays = [0 2.00e-5] sec Average path gain vector = [0 -9] dB

7.1. BER vs. SNR for OFDMA and SCFDMA

As seen in the figure 4. BPSK and QPSK have the lowest BER across all SNR values, making them most reliable modulations under noise. 16-QAM and 64-QAM offer higher data rates, but their BER performance degrades at lower SNR. The BER decreases with increasing SNR, including improved reliability as signal strength.

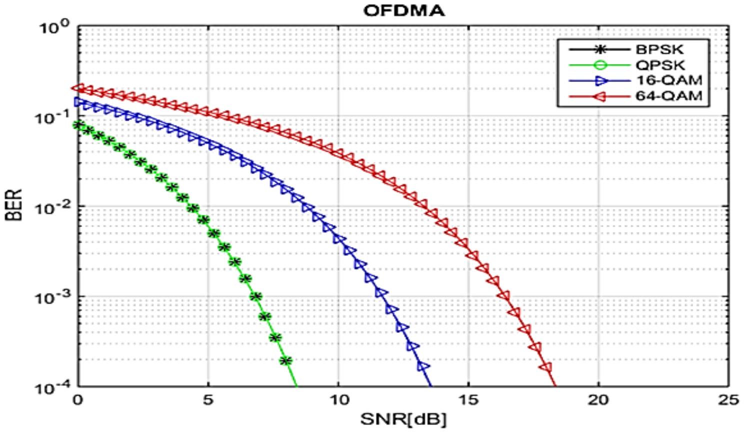

Figure 4 BER vs. SNR of OFDMA with Different Modulation

Figure 5 shows a similar BER VS. SNR plot, but for SC-FDMA , Again, BPSK provides the best BER performance. However, the BER curves in SCFDMA are generally better (lower) than in OFDMA for the same modulation types and SNR values because it

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has lower PAPR and makes it less sensitive to nonlinear distortion from amplifiers, especially in the uplink.

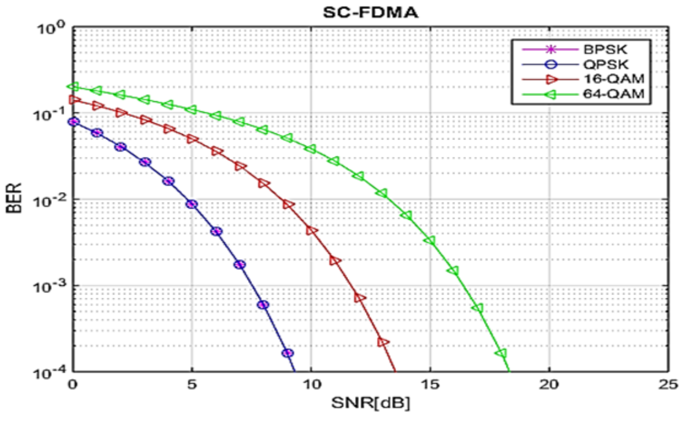

Figure 5 BER vs. SNR of SC-FDMA with Different Modulation

7.2. Probability of Error for SC-FDMA and OFDMA

Figure 6 shows the probability of error for OFDMA using BPSK, QPSK,16QAM and 64-QAM. Results show that the 64-QAM has the highest error probability, and 16QAM achieves better performance, whereas the QPSK and BPSK provides the lowest error rate among the compared schemes.

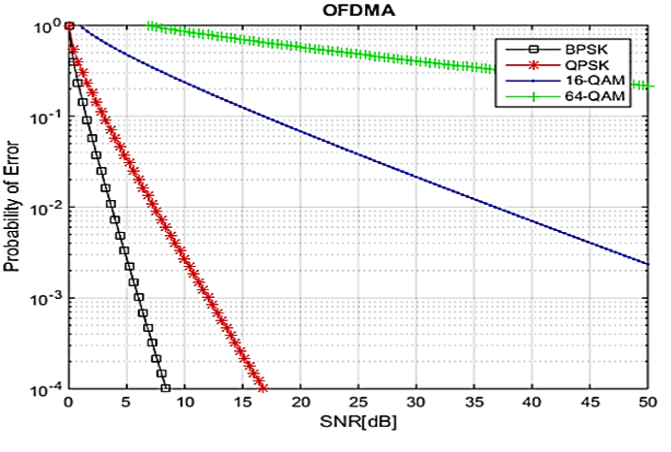

Figure 6 Error Probability of OFDMA With Different Modulation

Figure 7 shows the relationship between the probability of error and SNR for SCFDMA under different modulation schemes (BPSK, QPSK,16-QAM and 64-QAM). At a SNR value of 4dB, it is observed that 64-QAM exhibits the highest error probability,

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including its lower robustness to noise. In contrast, 16-QAM demonstrates better performance than 64-QAM but is still less than

QPSK and BPSK. Among all modulation schemes, BPSK achieves the lowest error probability, followed by QPSK, confirming their higher reliability under low SNR condition.

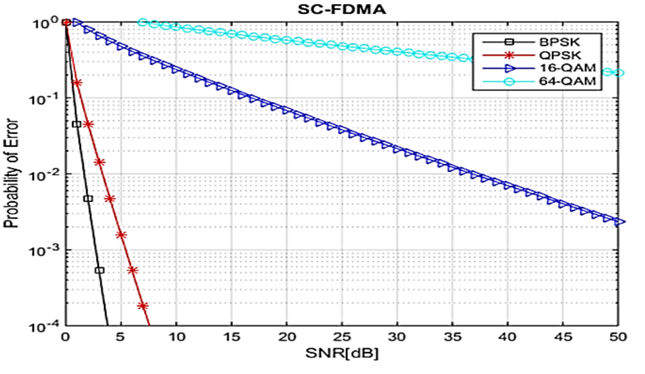

Figure 7 Error Probability of SC-FDMA With Different Modulation

7.3. Peak Average Power Ratio of OFDMA and SC-FDMA

In the figure 8 the red curve, representing SC-FDMA, is consistently positioned to the left of the black curve, which represents OFDMA. This indicates that for any given probability, SC-FDMA exhibits a significantly lower PAPR value compared to OFDMA. For instance, at a probability of 10^{-2}, the PAPR for SC-FDMA is approximately 7 dB, whereas for OFDMA, it Is around 9 dB. This demonstrates the inherent advantage of SC-FDMA in maintaining a lower peak power relative to Its average power.

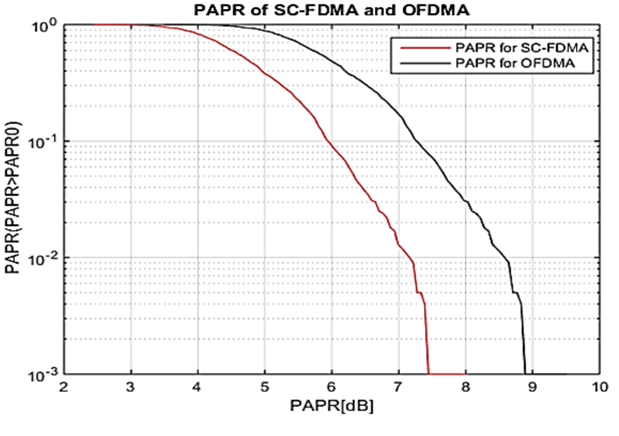

Figure 8 PAPR of OFDMA and SC-FDMA

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8. Conclusion

Bit Error Rate (BER) is a critical metric for assessing system performance. Our analysis indicates that the BER in Single Carrier Frequency Division Multiple Access (SC-FDMA) is lower and more efficient compared to Orthogonal Frequency Division Multiple Access (OFDMA). This efficiency arises because SC-FDMA allocates all data to a single subcarrier, unlike OFDMA, which distributes data across multiple subcarriers. Regarding Signal-to-Noise Ratio (SNR), OFDMA demonstrates superior efficiency across all modulation types due to its utilization of multiple subcarriers, which enhances performance particularly in higher-order modulation schemes. In terms of error probability, SC-FDMA consistently exhibits lower values than OFDMA across all modulation schemes, further underscoring its efficiency. When examining power spectral density, the average power of OFDMA symbols (512) exceeds that of SC-FDMA symbols across all frequencies, indicating greater efficiency for OFDMA in this aspect. Furthermore, the Peak-to-Average Power Ratio (PAPR) of SC-FDMA remains lower than that of OFDMA across all modulation schemes. This characteristic has led to the adoption of SC-FDMA for uplink transmission in Long-Term Evolution (LTE) systems. Based on these findings, we recommend employing lower-order modulation schemes, such as BPSK, QPSK, 16-QAM, and 64-QAM, for uplink transmissions to minimize PAPR at the user end.

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