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Original Article

Adaptive MIMO-OFDM Framework for Enhancing Wireless System Performance through Dynamic Modulation and Improved Spectral Efficiency

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Abstract *- This document Technological advancements allowing for high-performance mobile broadband Internet and real-time multimedia functionality are required across a range of devices due to technological advancements. LTE is a new standard for wireless communications, providing better throughput and spectrum efficiency than competing technologies. LTE utilizes OFDM and MIMO to meet the challenging data rate and throughput demands. MIMO is OFDM's inherent fading resistance and the high spectral efficiency, which make it desirable. Time and frequency dispersion cause intersymbol and intercarrier interference. Cyclic prefixes are used to mitigate intersymbol interference; OFDM is more spectrally inefficient as it is. FBMC is a viable candidate for future communication technology to mitigate OFDM spectral inefficiency. This research proposes an MIMO-FBMC to improve a MIMO system's performance under time-varying and time-dispersive channel scenarios. An adaptive filter design is also presented for MIMO-FBMC systems to operate effectively within doubly dispersive channels. Simulation outcomes show that the proposed MIMO-FBMC systems achieve significantly better performance in terms of throughput and BIT ERROR RATE when the system is configured to operate under the LTE standards*.

Keywords *- Long Term Evolution (LTE), Multiple-Input Multiple-Output (MIMO), Inter-Symbol Interference (ISI), Filter Bank Multi-carrier (FBMC), Bit Error Rate (BER), Cyclic Prefix (CP)*.

1. Introduction

The growth of the internet and other forms of wireless communication has opened up the modern industry to a massive new audience. The new wireless communication protocols have made it possible for consumers to utilize their gadgets globally. Increased demand for high data rates has spurred tremendous growth in the telecom sector in recent years. Most cutting-edge mobile communication apps need very high peak data rates, up to 1 Gbps in a stationary setting and 100 Mbps in a fast-moving one [1, 2].

Rapid innovation in the telecom sector is essential if the business is to meet the challenges of improving throughput and Quality of Service (QoS), which can only be achieved with the help of dependable and fast communication methods. That is why the strategies used must maximize efficiency in the use of the spectrum. High data rate transmission is limited by Inter-Symbol Interference (ISI), which is caused by multipath fading, another significant problem in wireless communication. If modern wireless communication systems are to meet the high standards of transmission quality that their consumers have grown to expect, they must first conquer a number of obstacles. Demand from users and new technology alike has been on the rise, making fourth-generation mobile communication systems an absolute need. Here, the new long-term evolutionary access technology known as Long Term Evolution (LTE) rose to prominence as the preferred network technology for 4G rollouts globally.

Thanks to its low-cost, high-speed data transmission, lightning-fast response, and enhanced network capacity, LTE is the perfect technology to meet the ever-increasing customer demand for mobile broadband services. With higher throughput, spectral efficiency, latency, and peak data rate, LTE aspires to provide better service quality compared to 3G systems. Among the most important aspects of modern physical layer system technologies is multi-carrier modulation (4CM).

The foundation of broadband systems, such as DSL, WLAN, and LTE, is based on multi-carrier systems like OFDM and FBMC [1, 2]. Optimal Frequency Division Multiplexing (OFDM) employs a redundant time gap known as a cyclic prefix between two symbols to address temporal dispersion and enhance per-carrier equalization [3, 4]. Due to the cyclic prefix's existence, transmission time is wasted, which in turn disrupts the low latency requirement, which in turn causes poor spectral efficiency and, finally, lower throughput [5]. An OFDM transmit and receive filter is a time-limited rectangular pulse with very large frequency-domain side-lobes, which leads to spectral leakage to neighboring sub-carriers. There will be Inter Carrier Interference (ICI) as a result of these emissions that are outside of the band.

Also limiting its usefulness in cognitive radio scenarios are the existence of big side-lobes. ICI is implemented in cases when the sub-carriers' orthogonality is disrupted due to rapid fading in mobile channels. The interference and ICI problems in OFDM, which occur under doubly dispersive channels with time and frequency spreading, require very strict synchronization approaches, which in turn increase power consumption [6].

Optimal Frequency Division Multiplexing (OFDM) works best under ideal channel circumstances because its subcarriers are orthogonal to one another. By comparison to the innovative services provided by 5G networks, the purported benefits and downsides of OFDM become moot. For the physical layer of 5G networks, researchers are now focusing on a more dynamic multi-carrier scheme, the FBMC system, which is seen as a potential contender. Flexible pulse shaping filters in FBMC are resistant against time-frequency dispersions induced by doubly dispersive channels and decrease out-of-band emissions. These filters are well-localized in both the time and frequency domains. Rapid service expansion, rising user numbers, multipath fading, and optimal spectrum usage are some of wireless communication's biggest obstacles [7].

Now more than ever, selecting the right modulation and multiple access techniques for mobile wireless communication systems is crucial for overcoming the aforementioned obstacles and achieving optimal system performance. A number of wireless applications have shown that parallel multi-carrier methods are more efficient in this sense. A frequency multiplex comprising parallel sub-channels that are not frequency selective (flat fading) is used in Orthogonal Frequency Division Multiplexing (OFDM). Sub channels in Orthogonal Frequency Division Multiplexing (OFDM) are designed to maximize spectral efficiency by eliminating the need to physically divide carriers using guard bands [8-11].

Even before Orthogonal Frequency Division Multiplexing (OFDM) methods were developed, multi-antenna approaches were recognized as a valuable tool for enhancing the performance of early line-of-sight systems and other general wireless communication networks. Modern Multiple-Input Multiple-Output (MIMO) technology is crucial to the most recent wireless communication standards for local area networks. One of the first wireless communication systems that included MIMO was LTE [12]. To address the complex and varied needs of future cellular networks, conventional OFDM has a number of limitations that make it an inadequate solution. These considerations prompted the author of this study to investigate the problems with the wireless system and provide suggestions on how to fix them. These are the first approaches to integrating multi-user scenarios onto MIMO-OFDM systems, and they also consider additional precoding improvements to the systems of interest.

The second part of the research is concerned with the introduction of the new scheduling algorithm [13, 14]. The algorithm allows the system to cater to different spatial and temporal user profiles, which is quite new. In this case, we jointly schedule and select MIMO transmission modes to optimize the LTE downlink performance for users with different mobility grades. These enhancements resulted in improvements of 27% in the average and 10th percentile of the cell throughput.

The LTE system toolbox provides a cellular system model that previous works have based their model on, and it is the ITU 3GPP spatial channel model. The performance of the system is also improved with the addition of turbo coding. Overall, the research is a contribution to knowledge on coded MIMO-FBMC systems, where we are curious to evaluate and contrast MIMO-OFDM and MIMO-FBMC. The proposed turbo-coded MIMO-FBMC system also demonstrates better performance in terms of BER when compared to the standard MIMO-OFDM system.

2. Classification of Channel Estimation Techniques

The initial classification of the channel estimation algorithm is illustrated in Figure 1. Some of these include: Decision Direct, Blind, Channel Estimate, and Pilot Based. Depending on the scenario, either comb-type or block-type pilots, together with data symbols, can execute the pilot-based channel estimation. In this scenario, block-type pilots send one single signal containing pilot subcarriers periodically. For channels with slow fading, this estimation performs satisfactorily as noted in [15].

For pilot estimation, however, a given number of frequency slots is allocated to introduce pilot tones with each OFDM signal. If the modifications are small enough to influence solely one OFDM block, then this channel estimation technique is ideal. Blind channel estimation is carried out by examining the available statistical data on the channel in addition to the distinctive features of the data transmitted. This technique of blind channel estimation is limited to the slowly-varying channels and does not consider the overhead erosion. However, in pilot channel estimation, the data stream is interleaved with known symbols to the receiver as training symbols or pilot tones [16]. LS, MSE, and MMSE are the other divisions of Pilot-Based Estimation. Frame Partitioning and Data Aided are subdivisions under Decision Direct. The blind channel has two sections, which are STBC and OSTBC [17].

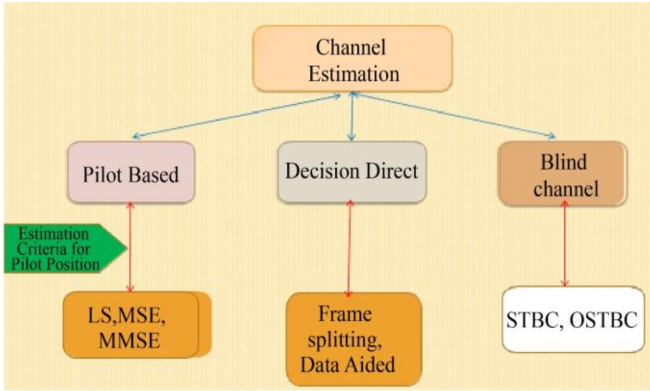

Fig. 1 Classification of channel estimation

For the pilot-based channel estimation, we have two subclasses: comb-type and block-type channel estimation. In block-type pilot-based channel estimation, all OFDM channel estimation symbol periods are transmitted. Because pilots are sent to all carriers, channel estimation accuracy will not be an issue, provided the channel remains constant during the block. Estimation can be performed using either LS or MMSE [18]. In comb-type pilot-based channel estimation, to estimate the channel for data sub-carriers using the channel information at pilot sub-carriers, an effective interpolation technique must be employed.

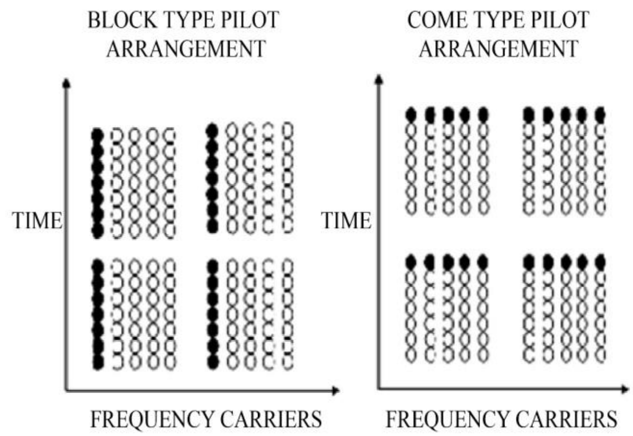

Fig. 2 Block-type and Comb-type pilot-based channel estimation

3. Literature Review

Reference	Key Contribution	Focus Area	Key Results / Insights
Kelvin Kuang-Chi Lee et al (2024) [1]	Proposed a Sub-Band Precoding (SBP) algorithm for wideband mmWave and THz M-MIMO-OFDM systems using fractional programming.	SBP for M-MIMO-OFDM systems	Reduced complexity by segmenting subcarriers into sub-bands; demonstrated sum-rate maximization through convex optimization.
Suhwan Jang et al (2024) [2]	Introduced inclusive polar-domain SOMP for near-field channel estimation in hybrid MIMO-OFDM systems.	Near-field channel estimation	Improved range estimation and surpassed traditional P-SOMP in accuracy for near-field MIMO-OFDM systems.
B. Sridhar et al (2024) [3]	Developed PAPR reduction techniques with synthetic disturbance signals for MIMO-OFDM systems.	PAPR reduction and MUI elimination	Enhanced signal PAPR and multiuser interference mitigation, improving power efficiency in Massive-MIMO OFDM.
Koji Nishibe et al (2024) [4]	Proposed a joint estimation method for channel and IQ imbalance using a novel time-domain impulse pilot design.	Channel estimation in MIMO-OFDM	Reduced pilot symbol requirement, improving efficiency and mitigating Inter-Carrier Interference (ICI).
SiTong Li et al (2024) [5]	Introduced the ZOA-CoSaMP algorithm for sparse signal recovery in MIMO-OFDM using compressed sensing theory.	Sparse signal recovery in MIMO-OFDM	Improved channel estimation accuracy using ZOA for atomic matching and variable step size strategies.

Ding Shi et al (2024) [6]	Presented a beam-structured channel estimation approach for HF skywave massive MIMO-OFDM systems.	Beam-structured channel estimation	Validated Space-Frequency-Time (SFT) domain estimator design with low complexity and performance optimization.
Bing Ren et al (2024) [7]	Proposed 4D2DConvNet for robust MIMO-OFDM modulation classification over 5G channels.	Automatic Modulation Classification (AMC)	Achieved classification accuracy >95% at SNR of 8 dB in 5G frequency-selective fading channels.
Yanyan Zhao et al (2023) [8]	Developed a Continuous Piecewise Linear Companding (CPLC) scheme for low-complexity PAPR reduction in MU-MIMO-OFDM systems.	PAPR reduction in MU-MIMO-OFDM	Demonstrated trade-offs between PAPR suppression, BER, and OOB radiation, optimizing system performance.
Bilal Saoud et al (2023) [9]	Simulated MIMO-OFDM system scenarios to study modulation impact on performance.	Modulation impact on MIMO-OFDM performance	Highlighted the reliability and modulation's significant impact on BER and overall system performance.
Munna Khan et al (2023) [10]	Proposed an ICI mitigation algorithm compatible with time-domain synchronous OFDM for MIMO-OFDM systems.	ICI mitigation in time-varying MIMO-OFDM	Effectively suppressed BER and MSE in time-varying linear channels, enhancing the reliability of high-speed transmissions.

The full benefits of MIMO-OFDM systems can be attained only when several issues related to the systems are resolved. Out of these issues, the need for precise Channel State Information (CSI), Inter-Carrier Interference (ICI), and high Peak-to-Average Power Ratio (PAPR) is of great concern [18-20]. The issues of communication, in such highly variable conditions, in the presence of mobility, interference, and the use of various channels in diverse time periods, can be potentially drastic. In response to such issues, innovative methodologies that allow real-time optimization of system parameters to satisfy the user and channel conditions were developed [21].

In MIMO-OFDM systems, various parameters are changed, including coding rates, modulation schemes, dynamic control of power allocation, and beamforming algorithms. Thus, by using advanced algorithms in signal processing and machine learning, these systems can achieve optimal levels of energy efficiency, throughput, spectrum efficiency, and BER. The use of adaptive techniques greatly decreases PAPR and ICI, along with communication reliability, no matter the conditions. Obtaining accurate and real-time channel state information to inform the optimal choice is key to the success of the adaptive MIMO-OFDM approach. There are multiple methods, like feedback systems, compressed sensing, and utilization of channel estimates, that can be used to acquire and utilize CSI.

Additionally, Adaptive MIMO-OFDM systems have become more appealing as potential solutions due to advancements in hardware technologies, such as programmable antennas and low-power RF circuits. One of the primary focuses of research is the creation of target-specific algorithms and models, specialized for mobile broadband and vehicle communication, as well as the Internet of Things [22-25]. Adaptive MIMO-OFDM systems have been confirmed in both simulations and deployments to have the potential to improve energy efficiency, reduce communication delays, and improve throughput.

The focus of the work is on the design and optimization of wireless communication systems using the Adaptive MIMO-OFDM technique. One of the primary aims of the work is to improve system parameters while addressing and providing new solutions to key challenges. By having deeply researched current trends and future possibilities [26]. Efficient design, new algorithm development, and performance assessment are balanced to meet today's wireless applications' needs and build fast, dependable, and resilient communication systems

4. Peak To Average Power Ratio (PAPR) of OFDM Systems

OFDM is a desirable modulation for high data rate transmission due to its numerous desirable characteristics. Having said that, there are a few of its inherent drawbacks as well. The transmitted signal's high Peak-to-Average Power Ratio (PAPR) is a big issue with OFDM at the transmitter. A possible formula for the peak power when all the subcarrier signals are constructively combined is the number of subcarriers multiplied by the average power. Peak power, rather than average power, is the primary determinant of a power amplifier's power usage [27]. The efficiency of the power amplifier is reduced, and the transmitted signal experiences non-linear distortion when the PAPR is large. Power amplifiers that are linear are wasteful and cannot handle these big peaks. We have to sometimes let the power amplifiers become saturated, which causes in-band distortion and out-of-band radiation, so we can avoid running the amplifiers with huge back-offs. In theory, the PAPR delta between OFDM and single-carrier systems grows in direct proportion to the sub-channel count, although in practice, this relationship is seldom satisfied [28].

Power Density Spectra (PDS) and error probabilities of non-linearly distorted OFDM signals have traditionally been found by analysis, simulation, or hybrid analytical simulation methods in order to evaluate their performance. A number of methods have been suggested for lowering the PAPR; they include partial transmit sequences, selective mapping, peak windowing, peak cancellation, and clipping. One way to make non-linearly distorted OFDM signals work better is to use PAPR reduction codes. To remove combinations that cause high peaks, PAPR reduction codes, for instance, add a set of redundant symbols to the data set [29].

One way to think about PAPR control systems is as a combination of synthesis and pre-distortion procedures. In order to lower PAPR, synthetic approaches alter or modify the source data or parameters while they are creating the broadcast signal. On the other hand, a pre-distortion strategy involves using signal processing techniques on the generated broadcast signals to reduce PAPR. Actually, some of these methods have been suggested for use in satellite communication. Nevertheless, synthetic methods have been suggested to address the PAPR issues with OFDM systems.

In these methods, a data frame's OFDM symbol is replicated many times, and the one with the lowest PAPR is sent. To further enhance the functionality of OFDM signals that are non-linearly distorted, pre-distortion methods have been suggested. The idea behind pre-distortion is to distort an OFDM signal before applying non-linear distortion to it; this will restore the signal to its original form [30]. With this analysis, we can foretell not only how many iterations will be needed to reach a certain threshold PAPR, but also the maximum PAPR that may be achieved within that time frame

5. Overview of PAPR in OFDM Systems

An Orthogonal Frequency Division Multiplexing (OFDM) signal is the combined signal of numerous subcarrier signals, each of which is modulated using a unique symbol. If we think of the data transmission as a random process, then the OFDM signal's amplitude is also a random process.

The central limit theorem states that as the number of subcarriers increases, it follows a complicated Gaussian distribution. The result is an extremely high peak-to-average power ratio in OFDM transmissions. Because the amplifier's maximum output power restricts the transmitter's ability to generate a very high signal amplitude, interference occurs in both the OFDM band and neighboring frequency bands. In OFDM, a block of N symbols, $\{D_n, n=0,1,2,3, \ldots, N-1\}$ is formed with each symbol modulating one of a set of subcarriers [31].

The N subcarriers chosen to be orthogonal, that is $f_n = n\Delta f$ where $\Delta f = 1/T_d$ and T_d, is the OFDM symbol duration. The resultant signal is supplemented with a cyclic prefix, sometimes known as a guard interval, to ward off the Intersymbol Interference (ISI) that manifests in multipath channels. Typically, the OFDM symbol is extended periodically to serve as the guard interval. At the receiver, the guard interval is removed, and the time interval [0, Td] is evaluated. Time-domain samples of OFDM signals in the equivalent complex-valued low-pass domain are approximately Gaussian distributed due to the statistical independence of carriers.

6. OFDM Model in Band Pass Non-Linearity

Figure 3 shows the OFDM signal model in band-pass non-linearity. It is believed that the OFDM signal has a small bandwidth in comparison to the center frequency. One traditional issue with signal transmission across amplitude-limiting channels is the study of narrow-band signals in band-pass non-linearity.

A broadband technique has recently been used to study OFDM's behavior under amplitude clipping [13]. Previous research failed to accurately measure in-band noise because it equated the distortion power in the first zonal area with the overall in-band noise power.

However, as shown here, a significant portion of the distortion energy is outside the OFDM signal band and may therefore be eliminated using filtering. Additionally, the interference distortion to neighbouring channels has not been quantitatively analyzed in the preliminary research.

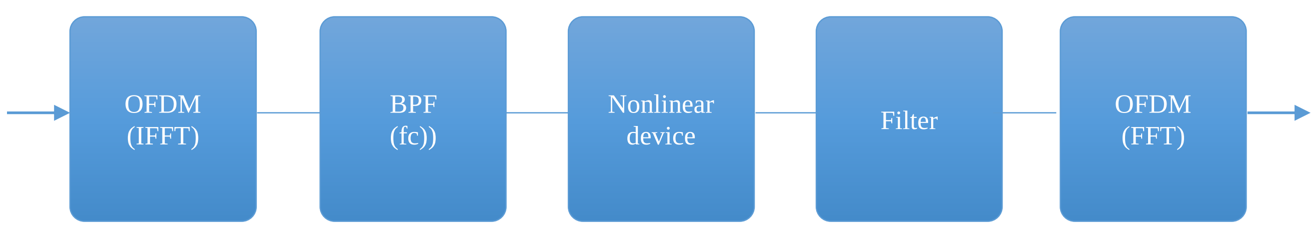

Fig. 3 OFDM model in band pass non-linearity

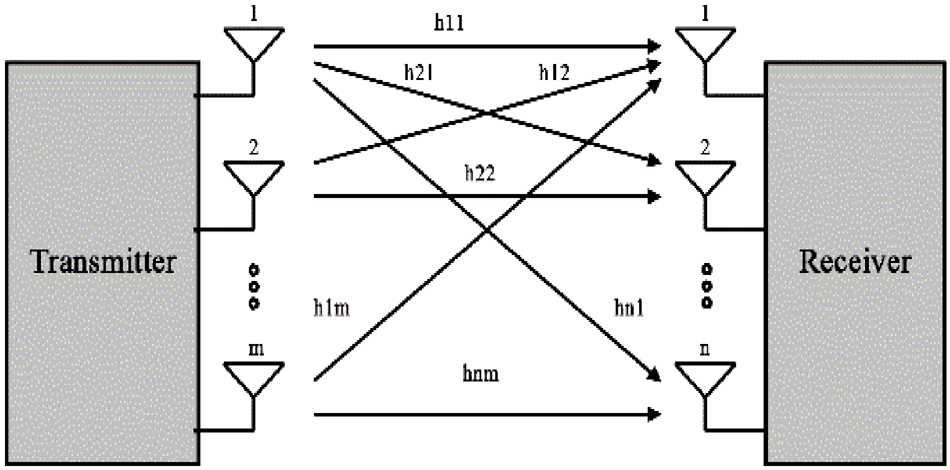

Fig. 4 MIMO system model with m transmit antennas and n receive antennas

7. Experimental Results

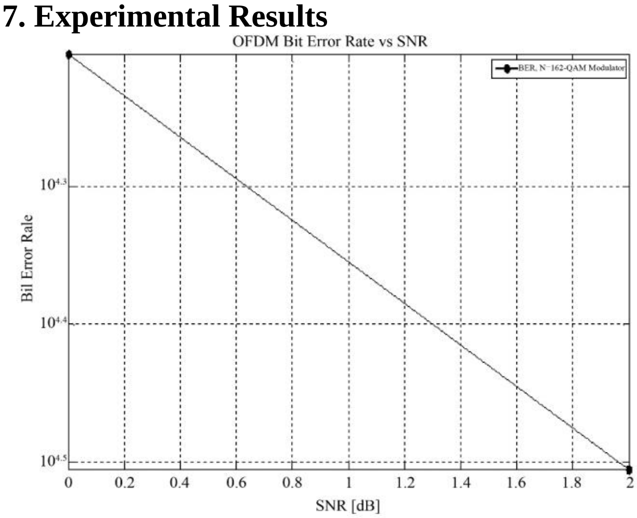

Fig. 5 BER vs. SNR performance curve for 16-QAM modulation

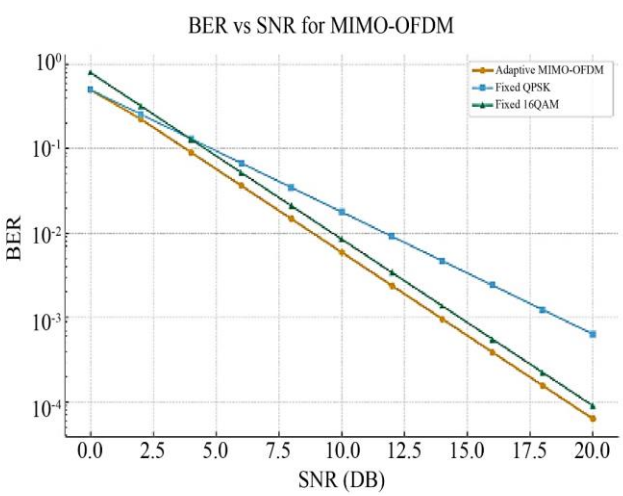

Fig. 6 BER vs SNR performance comparison for MIMO-OFDM

Figure 5 shows how the Bit Error Rate (BER) decreases as the Signal-to-Noise Ratio (SNR) increases for a 16-QAM modulator. It uses a logarithmic scale for BER, illustrating that as the communication channel becomes cleaner (higher SNR), the number of bit errors reduces significantly. The straight downward trend indicates the expected performance improvement of 16-QAM in AWGN channels. Higher SNR leads to more reliable data transmission with fewer errors.

Figure 6 illustrates the comparison between the Bit Error Rate (BER) performances of three different schemes: Adaptive MIMO-OFDM, Fixed QPSK, and Fixed 16-QAM at various Signal-to-Noise Ratio (SNR) values. With an increase in SNR, a corresponding decrease in BER is observed for all techniques. The adaptive MIMO-OFDM curve indicates a significantly lower BER as the system changes dynamically with modulation schemes depending on the channel conditions.

At high SNR, Fixed QPSK is the worst performer, while fixed 16-QAM is better but still behind the adaptive curve. In general, the graph portrays the extent to which an adaptive modulation in a MIMO-OFDM system can be relied upon for communication with a lower amount of bit errors.

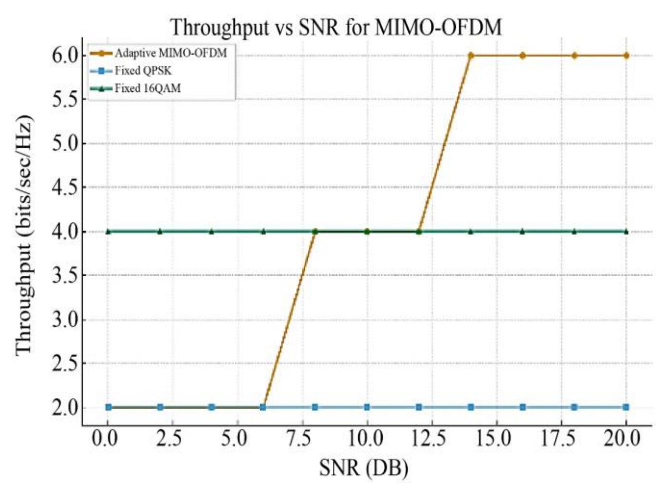

Fig. 7 Throughput vs SNR for MIMO-OFDM

The graph shown in Figure 7 illustrates the different kinds of throughput (in bits/sec/Hz) depending on SNR levels for the three types of schemes: Adaptive MIMO-OFDM, Fixed QPSK, and Fixed 16-QAM. SNR being low, Fixed QPSK is permanently fixed at 2 bps/Hz since it is using the same low modulation throughout the entire process. On the other hand, Fixed 16-QAM is also behaving like SNR is high, as it is always providing a higher capacity, and at the same time requiring better channel quality.

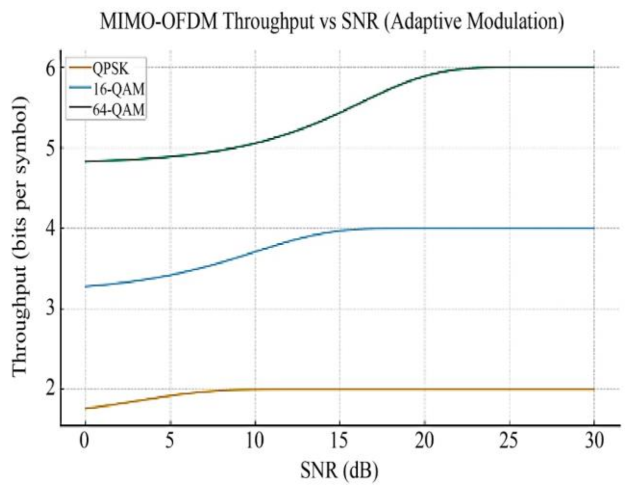

Fig. 8 MIMO-OFDM Throughput vs SNR (adaptive modulation)

Figure 8 shows the variation of a MIMO-OFDM system's throughput (measured in bits per symbol) with a rise in SNR (Signal-to-Noise Ratio) while different modulation schemes, QPSK, 16-QAM, and 64-QAM, are being employed. The adaptability of the modulation evidently enhances the system's capability since it chooses the best modulation according to the current situation. The SNR increase allows the system to move through the stages QPSK → 16-QAM → 64-QAM, thus reaching a substantially higher throughput, along with the reliability still preserved.

8. Conclusion

The MIMO-OFDM system with adaptive modulation analysis and simulation results has provided clear evidence that adaptive techniques can greatly improve the reliability and efficiency of today's wireless communication systems. The BER vs. SNR graphs make it clear that adaptive MIMO-OFDM is always more error-free than the fixed-modulation techniques like QPSK and 16-QAM. The system is able to preserve error-free communication even in low-SNR environments because of the intelligent switching of modulation levels according to channel conditions. Likewise, the Throughput vs. SNR graphs support the notion that it is the fault of adaptive modulation that the data rate has been maximized.

Fixed modulation schemes have a consistent throughput that is independent of channel quality, which affects the extractable bandwidth at high SNR. The opposite is the case with adaptive MIMO-OFDM, where increasing the throughput is a gradual process from QPSK to 16-QAM and finally to 64-QAM as SNR improves.

The dynamic adjustment is a key factor in achieving up to 6 bits per symbol and is thus a way of providing better spectral efficiency. The productivity graphs taken together prove that adaptive MIMO-OFDM offers a very good quality mixture of low BER and high throughput, making it a best-fit for next-generation high-capacity wireless networks. The system's capability of turning channel variations to its advantage and taking MIMO diversity to a higher level results in it being robust, having high spectral efficiency, and delivering data even in the most difficult wireless environments that are reliable.

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