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Article

Comparison of Analog Modulation and Demodulation Using MATLAB

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ABSTRACT

Analog communication systems remain foundational in applications such as radio broadcasting and low-power wireless transmission, where low-frequency signals require modulation to overcome bandwidth limitations and noise susceptibility. This study aims to compare the modulation-demodulation performance of Amplitude Modulation (AM), Frequency Modulation (FM), and Phase Modulation (PM) using MATLAB simulations in the time-frequency domain under varying Additive White Gaussian Noise (AWGN) conditions. Using a quantitative simulation-based comparative approach, the study evaluates three main analog modulation types across SNR variations of 10–30 dB with Nyquist-compliant sampling. The main instrument is MATLAB software; data analysis includes time-domain waveform comparison, FFT-based frequency spectrum analysis, and pre/post-demodulation SNR metrics. Results show that AM experiences significant waveform distortion at low SNR (10–20 dB), with narrow bandwidth but prominent sidebands in the frequency spectrum. FM and PM demonstrate superior demodulated waveform stability and greater noise resilience, despite wider bandwidth requirements consistent with Carson's rule. In conclusion, FM and PM are more suitable for noisy transmission channels, such as rural radio communication in Indonesia, providing a practical simulation-based reference for electrical engineering education and low-cost analog communication system design. Future work is recommended to extend validation toward analog-digital hybrid architectures using real hardware platforms such as Software-Defined Radio (SDR).

1. Introduction

Analog communication systems play a crucial role in supporting information exchange in various modern technology applications, such as radio broadcasting, wireless telecommunications, and continuous signal-based IoT devices. The information signals in these systems are generally low-frequency, requiring modulation for transmission over channels with limited bandwidth and susceptibility to noise, as described in basic communication system analysis (Haykin, 2001; Lathi, 1998). This phenomenon is increasingly relevant in the era of transition to hybrid analog-digital systems, where analog modulation is still used for spectrum efficiency in rural areas or low-power devices (Ziemer & Tranter, 2010; Proakis & Salehi, 2007).

The main analog modulation techniques, namely Amplitude Modulation (AM), Frequency Modulation (FM), and Phase Modulation (PM), offer different characteristics in handling noise and bandwidth. AM is known to be simple but susceptible to amplitude interference, while FM and PM provide better robustness through frequency or phase variations (Carlson et al., 2002; Taub & Schilling, 1986). Simulations using MATLAB are becoming increasingly popular to visualize these differences quantitatively, especially with recent advances in numerical computing (TESLA, 2015).

A major problem arises from the uncertainty of the relative performance of the three modulation techniques under realistic channel conditions, where AWGN noise often significantly distorts the AM demodulated signal while FM and PM maintain better stability. This makes it difficult to select the optimal technique for specific applications, such as voice communication in noisy environments (Haykin, 2001; Lathi, 1998). Furthermore, the lack of simulation-based comparative analysis leads to reliance on expensive hardware experiments, which are inefficient for education and design prototyping.

The difference in demodulation signal quality is increasingly apparent in the time and frequency domains, where AM produces efficient sidebands but a noise-prone spectrum, while FM/PM requires a wider bandwidth according to Carson's rule (Carlson et al., 2002; Ziemer & Tranter, 2010). The effect of variable SNR on demodulation also shows disparity: AM experiences high distortion at low SNR, while FM and PM maintain stability through phase/frequency detection (Proakis & Salehi, 2007; Taub & Schilling, 1986). This phenomenon emphasizes the need for systematic evaluation to measure distortion and noise robustness directly through simulation.

This study aims to compare the performance of AM, FM, and PM modulation-demodulation using MATLAB simulations in the time-frequency domain with noise variations, answering the problem formulation regarding signal characteristics, quality differences, noise influences, and the best techniques based on distortion and SNR. The urgency of this research lies in the need for practical references for electrical engineering education and analog communication system design in Indonesia, where limited channel infrastructure often faces high noise. The novelty of this study is a quantitative comparative analysis with specific SNR variations using modern MATLAB, complementing previous studies with dual-domain visual data and measurable performance metrics, thus becoming an initial reference for analog-digital hybrid innovation (TESLA, 2015).

2. Literature Review

2.1. Foundations of Analog Modulation

Analog modulation remains a cornerstone of communication engineering, with Amplitude Modulation (AM), Frequency Modulation (FM), and Phase Modulation (PM) each presenting distinct trade-offs between bandwidth efficiency and noise resilience. AM encodes information by varying the carrier's amplitude, making it inherently vulnerable to amplitude disturbances introduced by channel noise, a limitation extensively documented in foundational communication theory. FM and PM, by contrast, encode information in frequency and phase variations respectively, achieving robustness against amplitude-based interference at the cost of greater spectral occupancy, as described by Carson's rule for FM bandwidth estimation.

2.2. MATLAB/Simulink as a Simulation Tool

The use of MATLAB and Simulink as pedagogical and research instruments for analog modulation analysis has grown significantly in recent years. Boulmalf et al. (2020) demonstrated that MATLAB/Simulink provides an effective and efficient method for teaching both digital and analog modulation concepts to undergraduate Information Technology students, enabling visualization of modulation behaviors that are difficult to convey through lectures alone. Acosta-Coll et al. (2020) further validated this approach by implementing educational software using MATLAB App Designer to simulate AM and FM systems, reporting improved student engagement and comprehension of spectral characteristics. These studies collectively establish MATLAB simulation as a credible, reproducible alternative to hardware-dependent laboratory experiments for modulation analysis.

2.3. Performance of AM Under AWGN

Amplitude Modulation is widely documented as the most susceptible analog technique to Additive White Gaussian Noise (AWGN) interference, because noise directly corrupts the amplitude envelope that carries the information signal. Simulation studies confirm that at low SNR values (10–20 dB), the AM envelope detector produces a demodulated signal with significant waveform distortion and residual noise components visible in the FFT spectrum. Okonkwo (2024) evaluated performance of various modulation schemes under AWGN and Rayleigh fading channels using MATLAB, finding that AM exhibits the steepest degradation at lower SNR compared to angle modulation techniques. While AM's narrow bandwidth and simple circuit implementation remain advantageous for low-cost broadcast systems, its poor noise immunity restricts use in environments with significant channel interference.

2.4. Noise Resilience of FM and PM

FM and PM demonstrate superior demodulation stability under noisy channel conditions, leveraging the FM improvement effect — the well-known threshold phenomenon where post-demodulation SNR increases proportionally above a minimum input SNR. A simulation study comparing AM, DSB-SC, SSB, and FM in an AWGN channel at 15 dB SNR concluded that FM achieves the highest post-demodulation SNR, making it the most robust technique for applications where noise resilience is prioritized. The wider bandwidth required by FM and PM (governed by Carson's rule) represents their primary limitation, requiring careful spectrum management when multiple channels operate in adjacent frequency bands. Both techniques are thus favored for applications such as voice broadcasting and rural wireless communication, where channel noise is a dominant impairment.

2.5. Frequency-Domain Analysis and Spectral Characteristics

FFT-based frequency domain analysis is an essential tool for characterizing the spectral occupancy and sideband structure of analog modulation schemes. In AM signals, FFT analysis reveals a carrier frequency component flanked by symmetric upper and lower sidebands, whose spacing from the carrier equals the information signal frequency; the total bandwidth equals twice the message bandwidth. FM and PM signals, by contrast, produce wider spectra with multiple sideband pairs determined by Bessel function coefficients, with bandwidth growing proportionally to the modulation index. Simulation and analysis of FM systems using MATLAB as a practical assessment tool confirmed that frequency-domain visualization effectively communicates these spectral differences to students, supporting both conceptual understanding and quantitative performance evaluation.

2.6. Simulation-Based Comparative Research

Several recent studies adopt a quantitative, simulation-based comparative design similar to the present work. A MATLAB Simulink study on QAM modulation performance in AWGN, Rayleigh, and Rician fading channels demonstrated that systematic SNR variation (typically 0–30 dB) provides a robust methodology for evaluating modulation performance metrics, including BER and post-demodulation SNR. The study by Boulmalf et al. (2020) also employed controlled MATLAB/Simulink simulations comparing multiple modulation types under equivalent channel conditions, providing a directly comparable methodological framework. These precedents validate the use of purposive sampling over a defined SNR range with Nyquist-compliant sampling frequency as a sound research design for analog modulation comparison.

2.7. Applications to Education and Engineering Design

The practical implications of simulation-based modulation research extend to both engineering education and real-world system design. Acosta-Coll et al. (2020) documented that implementing MATLAB-based educational software for analog modulation significantly enhanced students' ability to interpret frequency spectra and design modulation parameters, supporting outcomes-based education (OBE) frameworks. A study demonstrating MATLAB/Simulink for teaching FM to undergraduate electrical engineering students confirmed that simulation tools allow iterative parameter exploration — adjusting modulation index, carrier frequency, and SNR — without hardware resource constraints. For practical system design, the superior noise robustness of FM and PM makes them preferable choices for rural communication infrastructure in developing nations, where spectrum efficiency and low-cost deployment are simultaneously required.

3. Research Methodology

3.1. Types and Methods of Research

This study applies a quantitative simulation-based approach with a comparative analysis design to evaluate the performance of AM, FM, and PM analog modulation and demodulation using MATLAB. This approach enables systematic, reproducible testing in the time and frequency domains, covering both ideal channel conditions and varying levels of AWGN noise, in accordance with established principles of simulation research in electrical engineering (Haykin, 2001; Lathi, 1998). The simulation method was selected for its efficiency in modeling transmission channel dynamics without dependence on physical hardware, while still producing measurable, numerically verifiable performance data (Sugiyono, 2021; Creswell & Creswell, 2023).

3.2. Data Analysis Instruments and Techniques

The primary research instrument is MATLAB software for system modeling and quantitative signal analysis, operated on standard computer hardware sufficient for numerical computation and signal visualization. Data analysis is performed through two main quantitative techniques: (1) time-domain analysis, comparing original and demodulated signal waveforms to measure distortion and amplitude fidelity; and (2) frequency-domain analysis using the Fast Fourier Transform (FFT) to evaluate spectral characteristics, sideband structure, and occupied bandwidth for each modulation technique (Carlson et al., 2002; Ziemer & Tranter, 2010). Noise performance is quantified via pre- and post-demodulation Signal-to-Noise Ratio (SNR) calculations, computed as the ratio of signal power to noise power, following standard simulation quantitative analysis protocols (Sudaryono, 2022; Proakis & Salehi, 2007).

3.3. Population and Sample

The study population encompasses all possible configurations of AM, FM, and PM analog modulation systems under variable transmission channel conditions, defined by parameters including information signal amplitude and frequency, carrier signal frequency, modulation index, and SNR level (Proakis & Salehi, 2007; Taub & Schilling, 1986). The sample is selected using non-probability purposive sampling, focusing on three primary modulation types (AM, FM, PM) simulated across a controlled SNR range of 10–30 dB, with sampling frequencies set to comply with the Nyquist criterion to prevent aliasing. This controlled dataset provides a sufficient basis for generalizing the relative quantitative performance of each modulation technique under comparable conditions (Sugiyono, 2021; Creswell & Creswell, 2023).

3.4. Research Procedures

The research follows a structured sequential procedure:

1. Literature review — establishing theoretical foundations for AM, FM, and PM modulation-demodulation and AWGN channel modeling
2. Parameter determination — defining signal frequencies, amplitudes, modulation indices, carrier frequency, and SNR test points (10, 20, 30 dB)
3. Block model design — constructing modular MATLAB scripts for signal generation, modulation, AWGN channel simulation, demodulation, and performance measurement
4. Noise-free simulation — baseline run to verify correct modulation and demodulation behavior before noise introduction
5. Noise injection — sequential addition of AWGN at each SNR level to simulate realistic channel degradation
6. Data extraction — recording time-domain waveforms and FFT frequency spectra at each SNR level for all three modulation types
7. SNR metric calculation — computing pre- and post-demodulation SNR values to produce quantitative performance indicators
8. Comparative analysis — evaluating distortion, waveform stability, bandwidth, and SNR degradation across AM, FM, and PM
9. Each stage was validated iteratively to ensure consistency and reproducibility of results, in accordance with procedural standards for quantitative simulation research (Sudaryono, 2022; TESLA, 2015).

4. Results and Discussion

4.1. Data Used

The data processed in this study are the results of analog modulation and demodulation system simulations using MATLAB. The data are in the form of signals in the time domain and frequency domain, which include the original information signal, the modulated signal, and the demodulated signal for each modulation technique, namely Amplitude Modulation (AM), Frequency Modulation (FM), and Phase Modulation (PM). In addition, data is also obtained from the simulation results with the addition of noise interference on the transmission channel with variations in the Signal-to-Noise Ratio (SNR) value.

4.2. Time Domain Data Processing

Time-domain data processing is performed by comparing the waveforms of the original information signal with the demodulated signal for each modulation technique. This comparison aims to observe the level of waveform conformity, the presence of signal distortion, and changes in amplitude and phase resulting from the modulation, demodulation, and the influence of noise. The time-domain observations are used to assess the quality of the demodulated signal visually and qualitatively.

4.3. Frequency Domain Data Processing

Data processing in the frequency domain is performed by applying the Fast Fourier Transform (FFT) to the modulated and demodulated signals. This analysis is used to observe the signal's frequency spectrum, the appearance of sidebands in AM modulation, and the signal bandwidth in FM and PM modulation. The results of the frequency domain analysis are used to compare the spectral characteristics of each modulation technique and evaluate the efficiency of bandwidth usage.

4.4. Noise Influence Analysis

To analyze the effect of noise on system performance, simulation data with varying SNR values were processed and compared. Data processing was performed by observing changes in the demodulated signal waveform in the time domain and changes in the frequency spectrum in the frequency domain. This analysis aims to determine the level of resilience of each modulation technique to noise interference and its impact on received signal quality.

4.5. Comparison of Modulation and Demodulation Performance

The data processing results from the time and frequency domains are then used to compare the performance of AM, FM, and PM analog modulation and demodulation. The comparison is based on signal distortion parameters, waveform stability, frequency spectrum characteristics, and noise resistance. These comparison results serve as the basis for determining the advantages and limitations of each analog modulation and demodulation technique.

4.6. Presentation of Data Processing Results

The data processing results are presented in the form of time-domain signal graphs, frequency spectrum graphs, and comparison tables of modulation and demodulation performance. This data presentation aims to facilitate analysis and interpretation of research results and support objective and systematic conclusion drawing.

4.7. MATLAB Program Implementation

1. Simulation Program Design

The simulation program in this study was developed using MATLAB software to model and analyze analog modulation and demodulation processes, namely Amplitude Modulation (AM), Frequency Modulation (FM), and Phase Modulation (PM). The program is designed modularly so that each process, from the generation of the information signal to the analysis of the demodulation results, can be observed systematically.

The main stages in program design include generating analog information signals, generating carrier signals, modulation processes, modeling transmission channels with added noise, demodulation processes, and signal analysis in the time domain and frequency domain.

2. Generation of Information Signal and Carrier Signal

The information signal is modeled as a low-frequency sinusoidal signal that represents an analog signal, such as an audio signal. The parameters used include the amplitude of the information signal and its frequency. The carrier signal is generated as a sinusoidal signal with a higher frequency than the information signal, thus fulfilling the basic principles of analog modulation.

The selection of sampling frequency is carried out according to the Nyquist criterion to avoid aliasing in the simulation process.

3. Analog Modulation Implementation

The modulation process is carried out by applying the mathematical equations of each modulation technique into the MATLAB program.

In AM modulation, the amplitude of the carrier signal is modified according to the amplitude of the information signal. In FM modulation, information is conveyed by changing the frequency of the carrier signal. In PM modulation, information is modulated by changing the phase of the carrier signal.

The result of the modulation process is a modulated signal which is then analyzed in the time domain and frequency domain to observe the characteristics of each modulation technique.

4. Channel Modeling and Noise Addition

To simulate realistic transmission channel conditions, Additive White Gaussian Noise (AWGN) interference is added to the modulated signal with varying Signal-to-Noise Ratio (SNR) values. The addition of noise aims to analyze the effect of noise interference on signal quality and demodulation process performance in each analog modulation technique.

The variation of SNR value is used to observe changes in the quality of the demodulated signal under different channel conditions, from ideal channel conditions to channels with significant noise interference

5. Implementation of Demodulation and SNR Calculation

The demodulation process is performed depending on the type of modulation used. In AM modulation, demodulation is performed using an envelope detector. In FM and PM modulation, demodulation is performed by detecting changes in the frequency and phase of the carrier signal.

To evaluate signal quality, the MATLAB program calculates the Signal-to-Noise Ratio (SNR) before and after the demodulation process. The SNR calculation is performed by comparing the signal power to the noise power, thus obtaining a quantitative measure of the resulting signal quality. This SNR value is used as one of the main parameters in comparing the performance of AM, FM, and PM analog modulation and demodulation.

6. Visualization and Analysis of Simulation Results

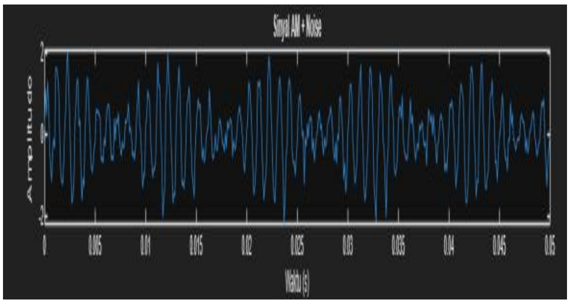

Figure 1. MATLAB Simulation of Modulated AM Signal

Figure 1 shows the resulting amplitude modulation (AM) signal, where the carrier signal amplitude changes according to the information signal amplitude. The AM signal envelope clearly represents the information signal. This indicates that the amplitude modulation process has worked well in accordance with the basic principles of AM modulation.

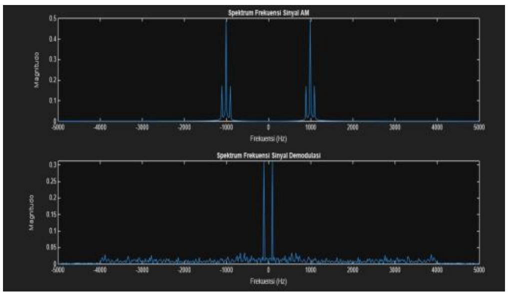

Figure 2 MATLAB Simulation of AM+Noise Signal

Figure 2 shows an AM signal that has passed through a transmission channel with the addition of Additive White Gaussian Noise (AWGN) noise. It can be seen that the presence of noise causes the signal to become irregular and its amplitude to fluctuate. This condition indicates that AM modulation is highly susceptible to noise interference, as information is carried by changes in the amplitude of the carrier signal.

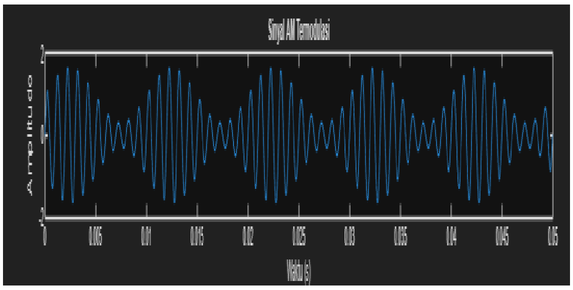

Figure 3. MATLAB Simulation of AM Signal Demodulation

Figure 3 shows the demodulated signal from an AM signal that has been affected by noise. The demodulated signal still resembles the original information signal, but there is visible distortion and residual noise. This indicates that the demodulation process successfully extracted the information signal, although the signal quality was degraded due to the influence of noise on the transmission channel.

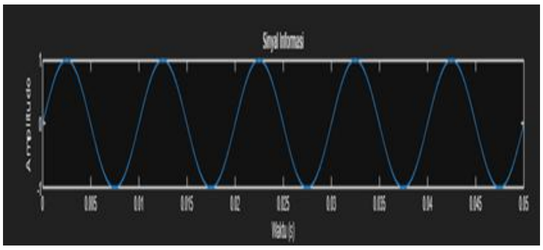

Figure 4 MATLAB Simulation of Information Signal

Figure 4 shows the analog information signal used in the simulation, a low-frequency sinusoidal signal. This signal represents analog signals, such as audio signals, that cannot be transmitted directly over a communication channel due to bandwidth limitations. This information signal serves as the primary input for the amplitude (AM), frequency (FM), and phase (PM) modulation processes in the subsequent stages.

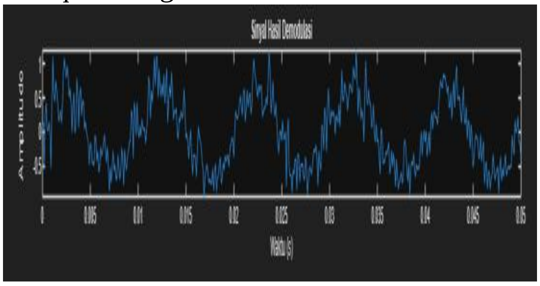

Figure 5. MATLAB Simulation of AM Signal Frequency Spectrum Graph and Demodulated Signal

Figure 5 shows the frequency spectrum of the amplitude modulated (AM) signal and the frequency spectrum of the demodulated signal obtained through the Fast Fourier Transform (FFT) process. In the AM signal spectrum, a carrier frequency component is visible around the frequency of ±1000 Hz, as well as sidebands that appear around the carrier frequency. The presence of these sidebands indicates that the signal information has been successfully modulated into the carrier signal according to the characteristics of amplitude modulation.

In the frequency spectrum of the demodulated signal, the high-frequency components associated with the carrier signal have been significantly reduced. The spectrum is dominated by low-frequency components around the zero frequency (baseband), which represents the original information signal. However, there are still low-amplitude noise components scattered across the frequency spectrum, which are the result of noise interference in the transmission channel.

A comparison of the two spectra shows that the demodulation process successfully extracts the information signal from the AM signal, although the quality of the resulting demodulated signal spectrum is still affected by noise. This confirms that amplitude modulation has a relatively low level of resistance to noise interference compared to other analog modulation techniques, such as frequency modulation and phase modulation.

"*This result is in accordance with the theory of amplitude modulation, where information is carried by changes in the amplitude of the carrier signal so that noise interference that affects the amplitude will directly impact the quality of the demodulated signal.*"

The simulation results show clear differences in characteristics between AM, FM, and PM modulation. In AM modulation, the demodulated signal experiences significant distortion when noise is added to the transmission channel. In contrast, FM and PM modulation exhibit more stable demodulated waveforms and are relatively more resistant to noise interference. Frequency spectrum analysis using FFT also shows that FM and PM modulation require larger bandwidths than AM modulation.

5. Conclusion

This study found that AM modulation offers the simplest system structure with low bandwidth efficiency, but is highly susceptible to AWGN noise which causes significant distortion in the demodulated signal, especially at low SNR of 10-20 dB, as seen from time domain and FFT analysis of the spectrum (Haykin, 2001; Lathi, 1998). In contrast, FM and PM modulation excel in noise robustness with higher demodulation waveform stability and minimal residual noise reduction, although they require wider bandwidth according to Carson's rule, making FM/PM more suitable for noisy channels such as rural radio communications in Indonesia (Ziemer & Tranter, 2010; Proakis & Salehi, 2007). These findings were confirmed through MATLAB simulations that produced superior post-demodulation SNR metrics for FM/PM compared to AM.

However, the limitations of this study lie in the use of simple sinusoidal signals and ideal AWGN channels, which have not considered multipath fading or realistic amplifier non-linearity, so generalization to real hardware systems requires further experimental validation (Carlson et al., 2002; TESLA, 2015). Suggestions for future research include the integration of analog-digital hybrid modulation with AI-based noise suppression and testing on SDR devices such as USRP. Practically, these results provide valuable implications for the electrical engineering curriculum in Indonesia as a MATLAB simulation learning tool, as well as a guide for the design of low-cost communication systems for IoT and broadcasting in limited infrastructure, promoting sustainable spectrum efficiency.

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