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Enhancing Angle Modulation Using Fractional Calculus: Theory and Performance Analysis

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Abstract: Angle modulation originally forms part of the backbone of the telecommunication and signal processing, where current studies are being carried out to improve its susceptibility to noise interference. This paper aims to analyze the possibility of the application of fractional calculus for optimization of angle modulation, as a requirement for development of enhanced and flexible communication networks. The main purpose of this study is to design and model new angle modulation technique which are Fractional Phase Modulation (FPM) and Fractional Frequency Modulation (FFM) by using fractional calculus. A generalized form of angle modulation and an introduction to the use of fractional calculus was proposed and a mathematical analysis of FM and FFM detectors was done. In evaluating the findings, the interaction between the fractional order of α and some performance parameters like Signal-to-Noise Ratio (SNR) and Figure of Merit (FoM) was also considered. It has been shown that FPM and FFM detectors also show high SNR and FOM performance, and when α is replaced. The FPM detector demonstrated a steady trend and increased from SNR 0 to 1 when the α was diverse, while the FFM detector had a huge increase in SNR from α=-0.9 to 0. These results indicate that the angle provides additional benefits in partial stones, signaling purity and system flexibility for the modulation technique. Thus, the ability to achieve better stability in communication for modulation techniques indicates the ability to achieve better stone purity and system flexibility for modulation techniques. Since partial order α can be adjusted to fit the application, the proposed method shows interesting applications in many communication settings, especially when the signal is noisy or dynamic.

Keywords: Angle modulation; Partial stones; Signal processing; Short reduction; Communication system; Adaptive modulation.

1. Introduction

The angular modulation acts as a basic technique within the framework of telecommunications and signal processing, which acts as a means to transfer information by manipulating a carrier wave phase or frequency. This manipulation is performed with accuracy to maintain the integrity of the signal between environmental conditions and noise. Unlike traditional methods such as import modulation (AM), angle modulation claims a number of benefits, especially in terms of noise flexibility and signal allegiance.

The essence of angular modulation lies in its ability to reduce the effect of variations, which often plague communication systems. When modifying the carrier wave phase or frequency, the angular modulation ensures that the indicated signal remains strong against the dimensions of the amplitude, which improves the clarity and fidelity of the transferred information, especially to the extent of sound transmission.

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In the frame of angular modulation, there are two separate techniques: Frequency modulation (FM) and phase modulation (PM). In FM, changes in the frequency of the carrier signal occur in direct correlation with changes in the dimension of the modulation signal [1] [2] [3]. This complex ratio means that ups and downs in the modulation signal, usually represent sound data, directly affect the frequency of the conveyor wave, and thus code information within its immediate frequency variations.

On the other hand, the phase modulation (PM) means manipulating the phase of the support signal in response to the dimensions of the modulation signal [4] [5] [6]. Like the amplitude of the modulating signal, the carrier wave phase leads to a nice coding of the information within the immediate phase changes of the signal.

The versatility of angular modulation extends only beyond theoretical structures, which find practical applications in a range of domains. From ubiquitous radio and two-way radio communication to complex complications of satellite communication and digital data transmission, the angle is an indispensable tool in the arsenal of modules and engineers, which strengthens long-distance, efficient, and effective communication in different environments.

In modern scientific and engineering subjects, partial calculation has increased as a widely used mathematical structure [8] [9 10] [10] [10] [10] [10] [11] [11] [11] [12]. In the core, the purpose of partial calculation is to expand the traditional prerequisites for discrimination and integration beyond the integer values, which is to present partial or non-reproductive order operators to adjust a wide range of mathematical operations and events.

Traditionally, Calculus belongs to the concepts of discrimination and integration, including mainly integer orders. However, many real-world events show behavior that cannot be described sufficiently with traditional calculus methods alone. Fractional calculus addresses this limitation by offering a more flexible and nuanced approach, enabling the analysis and modeling of complex systems with fractional dimensions or non-integer dynamics.

By introducing fractional order operators, fractional calculus provides a means to describe phenomena characterized by memory, hereditary properties, or fractal geometries, among others [13][14][15]. This mathematical framework has found applications across diverse fields such as physics, engineering, biology, finance, and signal processing, where traditional calculus may fall short in capturing the intricate dynamics at play.

The fractional operators are typically denoted by Dα for differentiation, where α is a fractional number Some common notions for fractional derivatives and integrals include the Grunwald-Letnikov, Regularized Liouville, Riemann-Liouville, and the Caputo fractional derivative, etc. [15][16][17].

$$\text{Grunwald} - \text{Letnikov}: \; D^{\alpha} f(t) = \lim_{|h| \to 0} \frac{1}{|h|^{\alpha}} \sum_{k=0}^{\infty} (-1)^k \binom{\alpha}{k} f(t - kh) \quad \forall\, \alpha \in \mathbb{R}^+ \tag{1}$$

Regularized Liouville:

$$D^{\alpha} f(t) = \frac{1}{\Gamma(-\alpha)} \int_0^{\infty} \tau^{-\alpha-1} \left[f(t - \tau) - \sum_{m=0}^{N-1} \frac{(-)^m f^{(m)}(t)}{m!} \tau^m \right] d\tau \quad \forall \alpha \in \mathbb{R}^+ \tag{2}$$

$$\text{Riemann} - \text{Liouville}: D^{\alpha} f(t) = \frac{1}{\Gamma(n-\alpha)} \frac{d^n}{dt^n} \int_0^t (t - \tau)^{n-\alpha-1} f(\tau) \; d\tau \quad \forall\, \alpha \in \mathbb{R}^+ \tag{3}$$

$$\text{Caputo derivative}: D^{\alpha} f(t) = \frac{1}{\Gamma(n-\alpha)} \int_0^t (t - \tau)^{n-\alpha-1} f^{(n)}(\tau) \; d\tau \quad \forall \alpha \in \mathbb{R}^+ \tag{4}$$

Most of the real physical phenomena can be accurately modelled using fractional calculus only; therefore, this mathematical concept is used to improve the performance of the system. In this letter, an attempt has been made to develop new angle modulation techniques using fractional calculus to avail the inherent aforementioned merits of this mathematical concept.

This paper is organized as follows: Section 2 is the literature review of angle modulation techniques literatures and other recent development in the field. The generalization scheme proposed in this paper and the signal transmission analysis to be employed in this study are explained in Section 3. In Section 4, signal detection is discussed more in-depth, and FPM as well as FFM detectors are introduced. Section 5 is devoted to the analysis of results and discussion: the comparison of FPM and FFM detector performance. The last Section 6 of the paper overviews the main findings of the discussion and indicates further research avenues.

2. Literature Review

Analog modulation can be traced back to work of Edwin Armstrong in the early 1930s when he developed frequency modulation, FM, to transform broadcasting technology. Armstrong wrote an article in 1936, in which the favorable properties of FM above AM were outlined, especially in the noise situation and the purity of the signal [1] [3]. His original research work laid the foundation for today's analog modulation schemes and is currently relevant to the development of communication systems.

The two authors, Lazzarini and Timoney, have recently provided a current advancement of this concept in using the higher-order frequency modulation synthesis. They have focused on techniques other than the basic ones for the generation and processing of signals for various applications [2].

Adequate efforts from boardmen and trees have responded with signals and noise interventions covering the angles of the message transfer, with an angular modulation applied to a sinus-shaped carrier while working with the Adat Gaussian channels. Basically, their work sets up the problem as a continuous power estimation one in which the objective is a waveform that is the MAP estimates of the message. The major contribution is obtaining the demodulator structure with delay, which makes the proposed realization of this optimal system feasible. Further, they discuss achieving higher efficiency and reliability of the obtained angle-modulated signals by using linear pre-emphasis applied to no-memory angle modulation [18].

The improvement in the phase modulation the flexibility of the techniques for signal transmission is a recent emphasis in advanced modernization. The improved power efficiency from amplitude and phase modulation high-purity work by Hati and Nelson is straightforward but practical in improving signal precision [4]. In the same way, Kim’s study on a phase modulator with variable maximum phase deviation is as an attempt to deal with the issue of modulation and the ability to change its parameters depending on the demand within a transmission [5].

Analogue modulation holds usefulness in the Internet of Things of (IoT) smart grid systems. Consistent with the objectives of the present paper, the study by Lv focuses on IoT as a communication means for various devices in smart city systems. This paper will discuss how IoT enhances power control through renewable energy sources, especially through frequency modulation. To overcome problems and issues related with installation of large amount of wind power, a new wind turbine control system approach, which utilizes frequency modulation methods such as the Pitch Angle Load Shedding is proposed [19].

Analyzing the main achievements of analog modulation, it is possible to admit that it has stimulated new breakthroughs in the spheres of biomedical and healthcare systems. The interesting application of modulation techniques in biomedical sensing has been demonstrated by Tong et al [20] on High-sensitivity Angle modulation biosensors based on surface plasmon resonance of meta surfaces. Furthermore, some recent difficulties and possibilities of modulation techniques for biomedical implanted devices are discussed by Hannan et al. in a profound literature overview. These studies pay much attention to choosing modulation types properly and designing signal processing algorithms to achieve a good performance of signal transmission and health monitoring and diagnosis in real time [21].

Another advantage of analog modulation has been seen in making available high-speed high-capacity communication system for providing multimedia facilities. The cross-sectional survey conducted by Ssimbwa et al. On the robust modulation requirements for 5G personal satellite communications has outlined some emerging custom in satellite-based communications. They have compared their modulation techniques with the traditional methods such as phase shift keying, continuous phase modulation, amplitude phase shift keying and quadrature amplitude modulation where the metrics such as the spectral efficiency, power efficiency and other parameters have been discussed. Continuous phase modulation stands out as the best strategy in terms of power efficiency, bandwidth efficiency, and error sensitivity [22][23].

Table 1. Key Contributions and applications of Analog Modulation Techniques in Communication Systems

Reference	Techniques	Key Contributions and Findings	Applications
[3]	Frequency Modulation (FM)	Introduced FM, and expounded on the benefits of using it over AM including, and especially in the reduction of noise.	Radio transmission, Communication systems
[2]	Higher-order Frequency Modulation	Extensively covered advanced FM techniques apart from the generated frequency signal processing methods.	Communication systems, Signal generation and processing
[4]	Phase Modulation Techniques	High efficiency methods for producing high purity amplitude and phase modulation has been evidenced, improving signal accuracy.	Signal processing, Communication systems
[5]	Variable Phase Deviation Modulator	Built a phase modulator with controllable maximum phase shift for maximum phase deviation; could be used where and when required.	Dynamic modulation in communication systems
[18]	Angle Modulation for Gaussian Noise Channels	Concentrated on passing analog messages through channels contaminated with Gaussian noise using angle modulation of a sinusoidal carrier. Created an actualizable demodulator configuration and suggested enhancements such as inner/outer linear pre-emphasis.	Efficient transmission of analog signals in noisy environments
[19]	IoT and Smart Grid Systems	Explored IoT's signal processing for communication between devices in smart cities with focus on frequency modulations for power control in RE systems. Distinct proposed control strategies of wind turbines using FM.	Smart grid systems, IoT, Renewable energy, Wind power management
[20]	Biomedical Sensing with Angle Modulation	Used high sensitivity angle modulation for biosensors especially for plasmonic meta surfaces for accurate measurements.	Biomedical sensing, Health monitoring
[21]	Modulation for Biomedical Implanted Devices	Examined modulation methods for biomedical implanted devices and discussed problems associated with the procedure, as well as guaranteeing reliability and real time signals of important physiological parameters.	Biomedical devices, Health monitoring, Medical diagnostics

Reference	Techniques	Key Contributions and Findings	Applications
[22]	Modulation in Satellite Communications	Studied and compared analyzed modulation techniques for next generation personal satellite communications in terms of spectral efficiency and power efficiency of per bit. The best to keep the power under control while still preserving a wide bandwidth and high error tolerance was found to be continuous phase modulation.	Satellite communication, Multimedia applications
[23]	Optical Systems and Modulation	Explored the properties of broadband and the incident angle modulation near-infrared polarizers and explicating the uses of modulation in optical communication systems.	Optical communication systems
[24]	Underwater Acoustic Communication	Discussed capacity optimization of underwater acoustic systems with special emphasis on problems associated with underwater communication.	Underwater communication systems
[25]	Underwater Visible Light Communication	Given potential modulation schemes for visible light communication system in underwater, providing solutions for underwater data transmission.	Underwater visible light communication
[26]	Satellite Communication and Modulation Signal Recognition	Studied the problems of modulation signal identification in underwater acoustic communication and proposed new approach to signal processing.	Satellite and underwater communication systems, Signal processing

To provide further evidence of the application of modulation techniques in advanced optical systems, the research of Guo et al. on broadband and incident-angle-modulation near-infrared polarizers supports the use of modulation techniques in recent communication systems [23].

There has been research exploration in other unusual applications such as underwater as well as satellite communication. As for the optimization of capacity for Underwater Acoustic Communication Systems, the research of Imran et al. captures major considerations of the underwater environment [24]. This category is the same as we are in the same way. Work on new methods for effective modulation of visible light for transferring underwater information [25].

Wang et al in satellite communication. In a difficult medium, acoustic communication modulation is underwater, with highly refined methods for signal recognition. Research on signal recognition. These activities can also aid in fine-tuning modulation aspects and strategies to increase performance and efficiency, which can support such applications as object identification, status, and high-speed grid connections, such as abundant surface cables and/or deficiency of telecom installations [26].

However, angular modulation is still a remarkable place to improve the plans, but calculus is not better used in this regard. Perhaps the appeal to partial stones in the design of these systems can dramatically increase the efficiency, strength, and versatility of analog communication transfer. A combination of such fresh techniques with classic modulation methods shows the possibility of progressive development of analog communication domains. It will also be clear that purification of analog modulation schemes and further improvement are inevitable when it comes to communication systems. Started with recent innovations in IoT with radio roots and Edwin Armstrong, biomedical application, and satellite communication analog modulation may be suitable for the modulation crisis. High-order frequency modulation, phase modulation, and angular modulation have been detected, and signal quality and spectrum use have improved, increasing the reliability of the system. In addition, there are potential good indications of improving the properties of traditional analog modulation techniques by incorporating partial calculation in the use of new techniques. With the tireless development of communication technologies, future research in this field will contribute significantly to the development of new generation, high-speed, high-capacity, and strong intervention mice communication systems.

The following table 1 provides an overall view and outline of the innovation and accomplishments with respect to the analog modulation techniques.

3. Methodology

The methodology as shown in figure 1 used involves generalization of the modulation scheme in which fractional calculus brings widened perspective of angle modulation. It combines

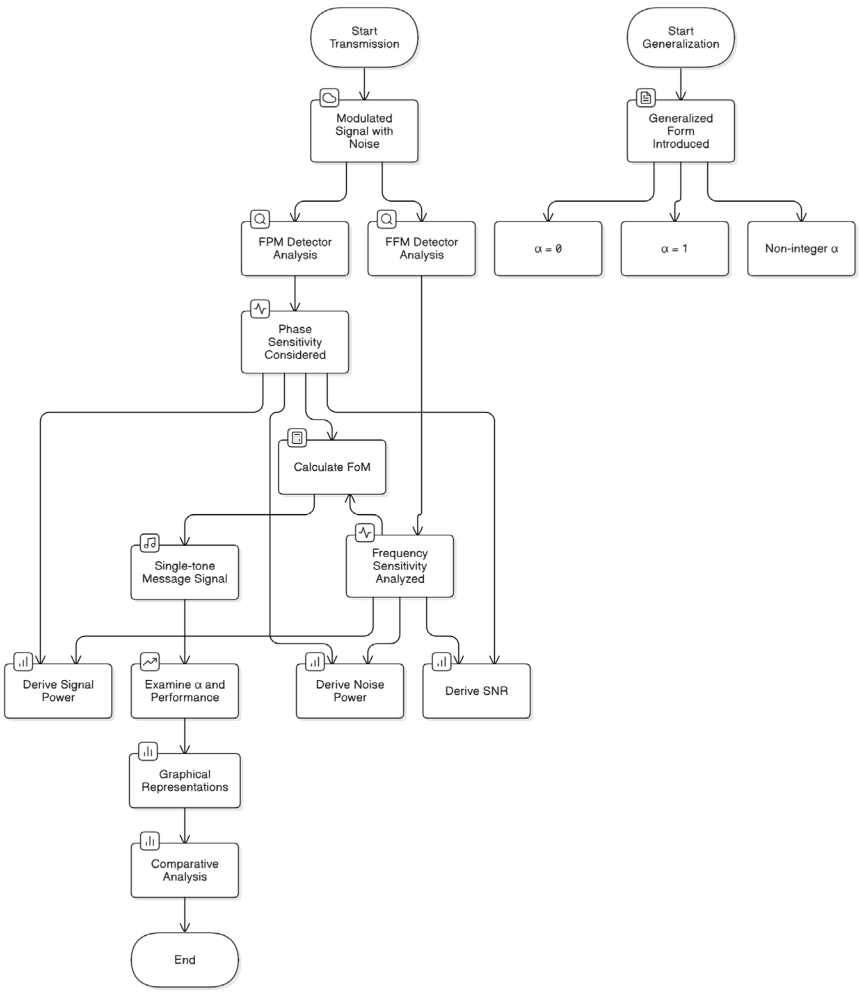

Figure.1. Flowgraph of the proposed methodology

Phase Modulation (PM), where α = 0 and Frequency Modulation (FM) where α = 1, while FPM and FFM represent α other than integers. Communication or signal transmission presupposes the presence of noise and contains a mathematical model of the received noisy signal. In the end, FPM and FFM detectors concerning the signal detection phase were compared. For FPM, phase sensitivity was investigated, together with equations for signal power, noise power and SNR and a FoM. In the same way, analysis of FFM detectors was aimed at frequency sensitivity, as well as at obtaining equivalent expressions for performance estimates. Performance analysis also evaluated the effects of α on both SNR and FoM based on graphical results. Finally, comparative analysis performed to compare the detector performances of FPM and FFM models.

A. Proposed Generalization Scheme

Let a message signal *m(t)* be applied to angle modulation with a carrier having amplitude *A* and oscillation frequency ω_c. This modulated signal can be generalized as:

$$V_\emptyset^f = Acos\{\omega_c t + K\, D_t^\alpha\{m(t)\}\} \qquad \forall\,(-1 < \alpha < 1) \tag{5}$$

It is important to note that this generalized fractional framework unifies conventional modulation schemes. When α = 0, the operator acts as a pure differentiator corresponding to Phase Modulation (PM), while α = 1 represents a complete frequency differentiation equivalent to Frequency Modulation (FM). For values of α between 0 and 1 (non-integers), the system exhibits intermediate characteristics, producing Fractional Phase Modulation (FPM) and Fractional Frequency Modulation (FFM). Hence, by continuously varying α, one can seamlessly combine PM and FM behaviors in a single mathematical formulation, offering a smooth transition and enhanced flexibility.

Here $D_t^\alpha\{\,\}$ is a generalized *diff-integrator* that acts as a derivative and as an anti-derivative (indefinite integral) for $\alpha > 0$ and $\alpha < 0$ respectively. The above-generalized equation represents a conventional PM (Phase Modulation) signal and conventional FM (Frequency Modulation) for $\alpha = 0$ and $\alpha = 1$ respectively. However, the non-integer values of α, above equation can be defined as FPM (Fractional Phase Modulation) and FFM (Fractional Frequency Modulation) for $0 < \alpha < 1$ and $-1 < \alpha < 0$ respectively. The instantaneous frequency of the modulated signal is :

$$\omega_i = \omega_c + KD_t^{1+\alpha}\{m(t)\} \tag{6}$$

It is also important to highlight that the bandwidth of the modulated signal depends jointly on the characteristics of the message signal m(t) and the fractional order α. A highly dynamic or wideband message signal naturally increases the required transmission bandwidth, and this effect is further influenced by the chosen fractional differentiation order. Larger α values enhance signal sharpness and detection performance but may demand broader bandwidth, whereas smaller α values conserve bandwidth at the cost of reduced noise robustness. Hence, the proposed fractional framework provides a means to wisely balance advanced performance improvements with the need for bandwidth efficiency by selecting appropriate α values.

Therefore, the bandwidth of the modulated signal depends not only upon the nature of message signal but also upon the order of differentiation. Further, the input signal power can be expressed as:

$$P_{S_i} = \frac{A^2}{2} \tag{7}$$

Considering uniformly distributed quadrature noise with PSD ℕ, within the transmission bandwidth $(\frac{-B_T}{2}\ to\ \frac{B_T}{2})$, the noise power at the input terminal is given as:

$$P_{n_i} = B_T\mathbb{N} \tag{8}$$

Thus, the signal-to-noise ratio (SNR_i) at the input terminal is:

$$SNR_i = \frac{A^2}{2B_T\mathbb{N}} \tag{9}$$

The entire communication process is divided into two parts: signal transmission and signal reception. The transmission action is discussed in section 3 whereas section 4 discusses the receiver action.

B. Signal Transmission

Assuming this modulated signal is encountered with noise *n(t)* during the transmission. So, a noisy signal is received at the receiver end that can be expressed by the following expression.

$$r_i(t) = V_\emptyset^f + n(t) \tag{10}$$

$$r_i(t) = A cos\{\omega_c t + K\, D_t^\alpha\{m(t)\}\} + r_n cos\{\omega_c t + \emptyset_n(t)\} \tag{11}$$

Here, r_n is associated with the variation in amplitude it possesses Rayleigh distribution, whereas $\emptyset_n(t)$ indicates noise phase and follows the uniform probability distribution. If $\emptyset_e(t)$ denote as $\emptyset_e(t) = \emptyset_n(t) - K\, D_t^{-\alpha}\{m(t)\}$. Thus equation (11) can be rewritten as:

$$r_i(t) = A cos\{\omega_c t + K\, D_t^\alpha\{m(t)\}\} + r_n cos\{\omega_c t + \emptyset_e(t) + K\, D_t^\alpha\{m(t)\}\} \tag{12a}$$

This equation can be further simplified as:

$$r_i(t) = [A + r_n cos\emptyset_e(t)] cos\{\omega_c t + K\, D_t^\alpha\{m(t)\}\} - r_n sin\emptyset_e(t)\, sin\{\omega_c t + K\, D_t^\alpha\{m(t)\}\} \tag{12b}$$

$$r_i(t) = R(t)\cos[\omega_c t + K\, D_t^\alpha\{m(t)\} + \theta_n(t)] \tag{12c}$$

where $R(t)$ is the amplitude of the received signal at the receiver's side and $\theta_n(t)$is the additional phase shift caused by noise, and expressed as:

$$\theta_n(t) = tan^{-1}\left\{\frac{r_n sin\emptyset_e(t)}{A + r_n cos\emptyset_e(t)}\right\} \tag{13}$$

The net effective phase at the receiver end is:

$$\psi(t) = K\, D_t^\alpha\{m(t)\} + \theta_n(t) \tag{14}$$

For higher CNR (Career to Noise Ratio) i.e. $A \gg r_n$, the phase shift $\theta_n(t)$ can be approximated as

$$\theta_n(t) = \frac{r_n}{A} sin\emptyset_e(t) \tag{15}$$

$$\psi(t) = K\, D_t^\alpha\{m(t)\} + \frac{r_n}{A} sin\emptyset_e(t) \tag{16}$$

C. Signal Detection

Now this modulated signal is detected at the receiver end through different types of detectors, i.e. FPM detector and FFM detector. Performance analysis of both detectors has been performed in the following subsections.

FPM Detector

The PM detector is sensitive to the phase of the received signal and the receiver gain is directly proportional to the phase as expressed below.

$$r_o(t) = \chi_p\, \psi(t) \tag{17}$$

$$r_o(t) = \chi_p \left\{K\, D_t^\alpha\{m(t)\} + \frac{r_n}{A} sin\emptyset_e(t)\right\} \tag{18}$$

At the receiver end, the signal component is given as:

$$s_o(t) = \chi_p\, K\, D_t^\alpha\{m(t)\} \tag{19}$$

Therefore, the signal power is given as:

$$P_{S_o} = {\chi_p}^2 K^2\, \overline{[D_t^\alpha\{m(t)\}]^2} \tag{20}$$

Similarly, the noise component can be expressed as:

$$n_o(t) = \chi_p \frac{r_n}{A} sin\emptyset_e(t) = \frac{\chi_p}{A} n_s(t) \tag{21}$$

Therefore, the output noise power spectral density is given as

$$S_{n_o}(f) = \left(\frac{\chi_p}{A}\right)^2 S_{ns}(f) \tag{22}$$

where $S_{ns}(f)$ is low pass quadrature noise $n_s(t)$ uniformly distributed over $\frac{-B_T}{2} < f < \frac{B_T}{2}$. However, the output is considered in the baseband (*i.e. –B to B*, where $B << B_T$) only, which gives the output noise as:

$$P_{n_o} = \left(\frac{\chi_p}{A}\right)^2 B\mathbb{N} \tag{23}$$

Thus, the signal-to-noise ratio (SNR_o) at the output terminal is:

$$SNR_o = \frac{{\chi_p}^2 K^2 \overline{[D_t^\alpha\{m(t)\}]^2}}{\left(\frac{\chi_p}{A}\right)^2 B\mathbb{N}} \tag{24}$$

So, the Figure of Merit (*FoM*) is:

$$FoM = 2K^2 \overline{[D_t^\alpha\{m(t)\}]^2} \left(\frac{B_T}{B}\right) \tag{25}$$

Here, signal-to-noise ratio and FoM depend upon the mean square of the fractional integration of the signal of order α. Further, a single-tone message signal defined as in (26) is taken into consideration. This single-tone message is trans-received using the proposed FPM scheme.

$$m(t) = A_m \cos(2\pi f_m t + \vartheta) \tag{26}$$

The SNR_o and FoM for the considered single-tone message signal are given as:

$$SNR_o = \frac{A^2 K^2 {A_m}^2 (2\pi f_m)^{2\alpha}}{2B\mathbb{N}} \tag{27}$$

$$FoM = K^2 {A_m}^2 (2\pi f_m)^{2\alpha} \left(\frac{B_T}{B}\right) \tag{28}$$

FFM Detector

Now, let us consider the FM receiving system which is sensitive to the frequency of the received signal, i.e. the output of the receiver is expressed as:

$$r_o(t) = \chi_f \frac{1}{2\pi}\frac{d\psi(t)}{dt} \tag{29}$$

$$r_o(t) = \frac{\chi_f}{2\pi} K D_t^{(1+\alpha)}\{m(t)\} + \frac{\chi_f}{2\pi} D_t\left\{\frac{r_n}{A} sin\emptyset_e(t)\right\} \tag{30}$$

So, $$P_{S_o} = \left(\frac{\chi_f}{2\pi}\right)^2 K^2 \overline{[D_t^{(1+\alpha)}\{m(t)\}]^2} \tag{31}$$

Noise is given by (32), and the corresponding spectrum is given by (33).

$$n_o = \frac{\chi_f}{2\pi} D_t\left\{\frac{r_n}{A} sin\emptyset_e(t)\right\} \tag{32}$$

$$S_{n_o}(f) = \left(\frac{\chi_f}{2\pi A}\right)^2 |j2\pi f|^2 S_{ns}(f) \tag{33}$$

Here, $S_{ns}(f)$ is given by $\mathbb{N}$, and constant over bandwidth *i.e. –B to B*. Since the noise spectrum is a parabolic function of frequency f, the total noise power is given by:

$$P_{n_o} = \left(\frac{\chi_f}{A}\right)^2 \frac{2}{3}\mathbb{N}B^3 \tag{34}$$

Thus, the signal-to-noise ratio (SNR_o) at the output terminal is:

$$SNR_o = \frac{A^2 3K^2 \overline{[D_t^{(1+\alpha)}\{m(t)\}]^2}}{8\pi^2 \mathbb{N} B^3} \tag{35}$$

So, the *Figure of Merit* is :

$$FoM = \frac{3}{4\pi^2 B^2} K^2 \overline{[D_t^{(1+\alpha)}\{m(t)\}]^2} \left(\frac{B_T}{B}\right) \tag{36}$$

In this case also, considering a single-tone message defined as in equation (26), the SNR_o and FoM are obtained as:

$$SNR_o = \frac{A^2 3K^2 {A_m}^2 (2\pi f_m)^{2(1+\alpha)}}{16\pi^2 \mathbb{N} B^3} \tag{37}$$

$$FoM = \frac{3}{8\pi^2 B^2} K^2 {A_m}^2 \ (2\pi f_m)^{2(1+\alpha)} \left(\frac{B_T}{B}\right)$$

4. Result and Discussion

The study examined two types of detectors for the modulated signal: Other kinds of the self-homodyne detectors include, Fractional Phase Modulation (FPM) detector and the Fractional Frequency Modulation (FFM) detector. In this particular case, the performance analysis of both detectors was informative and provided some additional understanding of their characteristics and operation.

A. FPM Detector Performance

The figure 2 illustrates the relationship between the fractional order α and two critical performance metrics: SNR for the FPM detector system and FoM for the FPM detector system. The SNR, shown as blue circles, increases continuously as α moves from 0 to 1, so the fractional system enhances the capability to suppress the noise when the fractional order increases. Such a trend implies that higher α increases the power of signal relative to noise hence improving the detection capability. On the other hand, the FoM represented by red diamonds experiences a slow decline as α increases, thus highlighting higher efficiency of the system. A lower FoM indicates improved system performance proving that modifying α not only increases SNR but also enhances the system's efficiency.

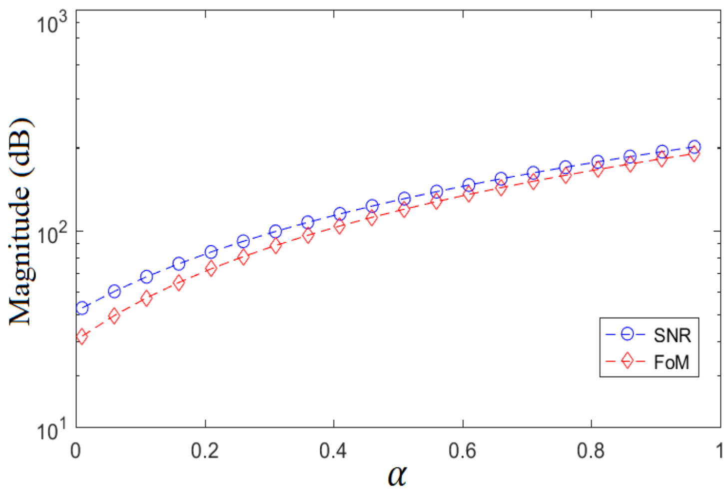

Figure 2. Variation of SNR and FoM for FPM.

The ability of regulating the noise performance is illustrated in figure 2, where the order of differentiation α determines the behavior of the system. This has been flexible in the proposed design where α can be tuned to improve on the performance of the PM scheme. Also, because signal bandwidth is determined by the nature of message signal m(t) and the order α, this technique is promising in increasing SNR and simultaneously maintaining the transmission bandwidth reasonable. These trends suggest that the control of the detection mechanism is highly dependent on partial order α. The performance properties of the system can be adjusted by adjusting α to the best point and providing a practical way to change environmental conditions with high noise or dynamic signals. The graphic results of the full duplex plan are in line with the signal force, theoretical values of noise power SNR, and figures for profits, which validate the efficiency of mathematical models that have been extracted for realistic FPM system design. The study suggests how the sensitivity reaction can be controlled through FOM and how it can be used to perform for performance benefits, and it is a tool that allows the user to adjust automatically to change signals. The findings of this article increase awareness of the importance of understanding and developing the noise for future development of the FPM detector system and the importance of increasing the signal quality.Understanding and developing noise robustness and enhanced signal quality is of high significance for the future development of FPM detector systems. Since FPM inherently allows α to be tuned continuously, future communication systems can exploit this flexibility to achieve resilient detection in environments with unpredictable or heavy noise. Improved robustness not only enhances SNR performance but also ensures reliable communication quality, making FPM detectors particularly suitable for advanced applications such as 5G, IoT, and mission-critical wireless networks.

The observed improvement in detection capability with increasing α can be justified by the fact that higher fractional orders emphasize the derivative (differentiation) component of the modulated signal, which inherently strengthens the instantaneous changes of the carrier. This has the effect of amplifying the useful signal energy while simultaneously reducing the contribution of low-frequency noise terms that are less responsive to fractional differentiation. As a result, when α increases, the signal-to-noise ratio rises because the signal power becomes more dominant relative to noise, thereby enhancing the detection capability of the system. Moreover, the performance characteristics of the system can be further optimized by finely adjusting α in very small increments. This fine-tuning mechanism provides a convenient adaptive strategy, allowing the detector to respond to changing environmental conditions such as high-noise channels or rapidly varying dynamic signals. By carefully selecting fractional values of α close to the optimal point, the system can balance noise suppression with bandwidth efficiency, thereby ensuring robust operation even under adverse transmission conditions.

B. FFM Detector Performance

In Figure 3, the order α is plotted against the SNR and FOM performance of the FFM detector. The graph shown below highlights several aspects that are of concern in the way the functionality of the FFM detector is affected by changes in α. Similarly, SNR marked with a blue circle was observed, while α is replaced from -0.9 to 0. This growing trend suggests that high partial orders improve the noise rejection capacity of the system, which leads to better detection capacity. As shown in the graph, α effectively contributes to the increase in noise conditions to signal power, which is very important if the signals need to penetrate the noise environment.

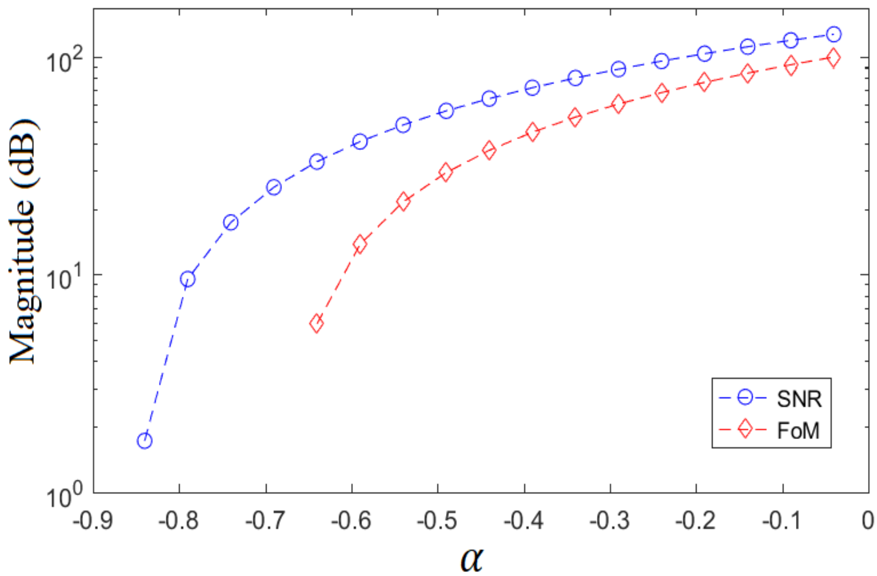

Figure 3. Variation of SNR and FoM for FFM.

Likewise, FoM, shown with red diamonds, decreases as α reduces to zero gradually. Thus, a lower value of FoM indicates better efficiency of the overall system and confirms that optimizing the fractional order allows system performance to be increased. This implies that although the adopted FFM design has a fixed α, this can be altered in order to fine tune the acoustic and perform abilities while attaining optimum SNR and FoM. The rapid increase in SNR in the FFM detector changes from −0.9 to 0 as α; this can be explained by changing how partial integration and discrimination are treated in noise. On negative α values, the system behaves more as a variable integrator, which accumulates noise energy and reduces effective SNR. When α reaches zero from the negative side, the noise sharing effect decreases, and the detector is transferred to a balanced position that favors discrimination against integration. This change increases the rejection of the noise dramatically, resulting in a standing increase in SNR because α is a zero approach. The most important thing is that the use of partial scheme modulation as a flexible instrument to achieve extended SNR and FOM does not unconsciously charge the transmission bandwidth. This message makes the dependency on signal tape width on the nature of signal M [T] and α, and it is important to prevent the system from using bandwidth when improving performance. This allows the proposed FFM design to function under individual signals and noise conditions, as they are favorable in the real application.

The graphic representation shown in Figure 3 is in good agreement with the theoretical results associated with signal power, noise power, SNR, and FOM, and validates the mathematical model. From this analysis an important aspect of tuning the system is the fractional order α, which has been presented here as a method for optimizing the detection performances. Combined, the findings presented in this work provide evidence of the benefits of using FFM as a method of flagging errors in signal processing since the FFM detector relied on the fractional order modulation that enhanced its performance.

C. Comparison Analysis of FPM and FFM Detector Performance

As α approaches 0 from −0.9, the FFM detector exhibits a sharp rise in SNR. This behavior can be attributed to the fact that negative fractional orders emphasize the integral (smoothing) characteristics of the signal, which inherently carry more noise components. As α increases towards zero, the system transitions from a noise-dominated fractional integration regime to a balanced derivative-integral regime, thereby dramatically suppressing noise. Consequently, the signal power becomes more dominant relative to noise, leading to a steep improvement in SNR when α approaches 0 from the negative side. Making a comparative analysis of the performance of FPM and FFM detectors from the results shown in the study, the following insights can be drawn about detector types:

By observing the SNR performance, it is clear that both detectors demonstrate enhancements as the fractional order α is varied, but in varying extents. A detailed analysis of the FPM detector shows a gradual increase in SNR from 0 to 1, which suggests even better noise reduction capacity as the fractional order increases. On the other hand, the FFM detector reveals a sharp raise of the SNR with α transformed from -0.9 to 0, which indicates that the rejection of noise is enhanced dramatically as the fractional order approximates to zero from the negative side.

The FoM for both the detectors indicate a similar trend in the detectors as depicted below. However, for the FPM detector, it was observed that FOM gradually decreases with the increase of α, while in the case of the FFM detector, FOM gradually decreases because α reaches zero. In both examples, such patterns suggest better system efficiency with variation in partial order. It is stated that one of the largest forces for both FPM and FFM systems is that they can be kept to a considerable extent. The flexibility of the partial order α allows fine adjustment of the detection strategy to increase the system's reaction during ups and downs in the environmental effects or signaling properties. This flexibility is especially useful in behavior when the signal-to-score is more or less than the ideal.

In particular, both systems reveal the possibility of better performance without affecting the transmission channel's bandwidth incorrectly. Therefore, the signal tape width depends on both the signal M (T) and the nature of the partial order α, which is found in the direction of wise production on the balance between profitable weight, advanced performance, and distributed bandwidth skills. From comparative results, it is clear that SNR behavior varies in two partial detector schemes. For the FPM detector, SNR gradually increases and varies continuously from

0 to 1 in the form of α. This is because high α values increase discrimination, strengthening the signal force compared to noise in a progressive way. In contrast, the FFM detector shows a rapid increase in SNR because α is 0.9 from 0.9. On negative α, the system accumulates noise energy due to the integrators, but since A is set to zero, it reduces accumulation, resulting in a dramatic improvement in noise rejection and thus increases the SNR. These supplements show that FPM provides stable performance benefits with α> 0, while FFM provides significant noise oppression benefits such as → 0 from the negative side. The result of the comparison of FPM and FFM detectors is shown in Table 2. It shows the trend in SNR, FOM, noise rejection, system efficiency, flexibility, as well as bandwidth effect on different intestines α. This comparison will prove that both detectors are favorable types and contribute to better performance.

Table 2. Performance comparison between FPM and FFM Detector

Performance Metric	FPM Detector	FFM Detector
SNR Trend	Gradual increase as α varies from 0 to 1	Sharp increase as α approaches 0 from -0.9
FoM Trend	Slow decrease with increase of α	Slow decrease as α approaches zero
Noise Rejection	Improves as fractional order increases	Enhances dramatically as α approaches zero from the negative side
System Efficiency	Improves with variations in fractional order	Improves with variations in fractional order
Flexibility	Can be fine-tuned using fractional order α	Can be fine-tuned using fractional order α
Bandwidth Impact	Maintains reasonable transmission bandwidth	Maintains reasonable transmission bandwidth

5. Conclusion

This study introduced a preferred way to improve angular modulation techniques through partial calculus, which means reducing noise and improving signal quality in communication systems. The work added a generalized angular modulation form using FPM and FFM techniques that led to partial calculus. Important comments suggest that both FPM and FFM detectors have increased SNR and FOM performance changes, which are separate -party -party order α. The results indicated that the FPM detector expanded SNR as α, as α was from 0 to 1, and the FFM detector extended SNR reaches near α-0.9 to 0.

Current research has a deep implication for the telecommunications industry. This fact of the adjustable partial order α presents a great advantage of flexibility that allows the system to set for its best performance in a certain environment and signal properties that are difficult to control. Such adaptability can also mean the development of speech treatment in the noise environment and the development of more effective turns in or rapidly changing signals. However, many restrictions in the study are clear. The evaluation was mainly performed in a theoretical approach associated with a mathematically produced model. The study gained evidence of the practical viability of partially calculus-based modulation techniques; However, more realistic applications and experiments will be necessary. The purpose of future studies should aim to find many real-life applications of FPM and FFM systems, where different environments are tested in an empirical research environment. In addition, it is also eligible to investigate the use of these methods for new technologies, such as 5G, IoT, etc. Therefore, this article has a valuable attachment to the area of angle modulation because it makes it clear how partial calculation can be used to improve signal quality and configuration to set more efficient and versatile communication systems. Thus, at the best point, the flexibility provides a practical passage for adaptive modulation, which enables noise and reliable performance in the dynamic environment. Thus, at the best point, the flexibility provides a practical passage for adaptive modulation, which enables noise and reliable performance in the dynamic environment.

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7. References

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