BirEx JOURNAL
Budapest International Research in Exact Sciences
Medical, Biological, Argiculture, Engineering Science and other related areas
e-ISSN : 2655-7827
p-ISSN : 2655-7835
http://www.bircu-journal.com/index.php/birex

Enhancing Communication Performance: Addressing Propagation Effects and Noise Sources

Belay Sitotaw Goshu
Department of Physics, Dire Dawa University, Dire Dawa, Ethiopia
belaysitotaw@gmail.com

Abstract: *This study investigates signal attenuation and chromatic dispersion, employing mitigation strategies to enhance signal quality in optical fibers. The results demonstrate that the original signal exhibits uniform propagation, but interference from noise leads to increased signal degradation, as indicated by the signal-to-noise ratio (SNR) statistics. The mean SNR of the original signal was 3.4147 dB, which increased to 5.0549 dB under noisy conditions. The SNR sharply dropped to -5.2713 dB after applying quantum squeezing techniques, indicating a discernible loss and a noise reduction. The SNR was raised to -4.8290 dB after noise filtration, suggesting a high performance but still below the initial signal quality. The effectiveness of the techniques was demonstrated through statistical analysis, including a t-test, which revealed variations in SNR under different conditions. Additionally, SNR variation with distance was explored, showing an increase proportional to the square of the distance, underscoring the need for distance considerations in optical communication design. Overall, this research provides insights into the complex interplay between signal enhancement methods and their impact on optical fiber communications.*

Keywords: *signal attenuation, chromatic dispersion, quantum squeezing, signal-to-noise ratio (SNR), optical fiber communication*

I. Introduction

The rapid advancement of communication technologies has revolutionized how information is transmitted and received, enabling high-speed connectivity across vast distances. However, the performance of optical and wireless communication systems is hindered by various challenges, including propagation effects, noise sources, and channel impairments. Understanding these factors is essential for designing more efficient communication systems. This study analyzes the significant propagation dynamics and noise challenges in optical and wireless channels, identifying effective strategies for enhancing communication performance. By addressing these issues, the research seeks to contribute to robust communication frameworks that can support the increasing demand for data transmission in modern society.

1.1 Background of the Study

Effective signal transmission over different channels, such as radio waves and optical fibers, is intrinsic to communication systems. The propagation of signals is affected by several factors, such as environmental conditions, limitations of the devices, and characteristics of the communication channel. Wireless communications are challenged by multipath propagation, fading, and interference, while attenuation and dispersion can severely reduce the integrity of signals in optical communications. Understanding and reducing the adverse effects of noise and channel impairments becomes crucial as data demands rise,

DOI: *https://doi.org/10.33258/birex.v6i4.8001*

especially with the growth of the Internet of Things (IoT) devices and high-definition multimedia (Dahlman et al., 2019; Rappaport et al., 2021).

Wireless communication systems have become integral in modern technology, supporting various applications from mobile communications to data transfer in remote sensing and satellite systems. As the demand for high-quality, reliable communication grows, so does the need to optimize signal transmission by minimizing noise and interference. The signal-to-noise ratio (SNR) plays a critical role in determining the efficiency and clarity of communication systems, as it measures the ratio of the power of a signal to the power of background noise (Goldsmith, 2005). A high SNR indicates better signal quality, while a low SNR suggests noise and interference dominate the communication channel, leading to potential loss and degraded performance.

Interference from adjacent users, ambient conditions, and technical constraints is one of the main problems with wireless communication since it can significantly lower SNR. Co-channel interference and other noise sources can cause the signal quality to decrease when numerous users share a communication channel (Rappaport, 2016). This issue is particularly relevant in densely populated areas, where the users lead to a significant decline in SNR.

There are now ways to enhance communication quality thanks to developments in noise reduction, antenna design, and modulation techniques. To improve SNR and lessen the effect of noise, methods like adaptive filtering, quantum squeezing, and multiple-input multiple-output (MIMO) systems have been proposed (Tse & Viswanath, 2005). Understanding potential ways to decrease noise and interference is crucial to developing dependable wireless communication systems that meet the ever-increasing demands of modern applications.

1.2 Statement of the Problem

Despite ongoing advancements in communication technology, many systems still suffer from significant performance limitations due to propagation effects and noise sources. Optical communication systems experience signal degradation through attenuation, dispersion, and nonlinear effects, leading to diminished signal integrity over long distances. For instance, Khan et al. (2020) emphasize that attenuation in fiber optic cables can reach up to 0.2 dB/km, significantly impacting long-haul communication links. Additionally, chromatic dispersion can result in pulse broadening, causing overlapping of signals and increased bit error rates (Wang et al., 2020).

Specific difficulties for wireless communication systems arise from environmental factors, including fading and multipath propagation. Urban surroundings frequently introduce reflections and diffractions in multipath effects that can deteriorate the quality of received signals (Rappaport et al., 2021). Moreover, a significant danger to the integrity of data transmission arises from interference from other devices using the same frequency band. This problem has been caused by the growth of the Internet of Things (IoT) since the density of linked devices raises the possibility of interference (Dahlman et al., 2019).

Moreover, the performance of optical and wireless systems can be further jeopardized by diverse noise sources, including shot noise, thermal noise, and intermodulation noise. The threshold for signal-to-noise ratios is defined by Zhang et al. (2021), who point out that thermal noise caused by the random motion of charge carriers is a core constraint in electronic components used in communication systems. Shot noise, which arises from the quantized character of light in optical systems, can have the foremost effect on performance, particularly in low light (Wang et al., 2020).

These impairments' combined impact may result in higher mistake rates, lower data rates, and erratic connections all of which are stern issues in high-speed networks for communication. It is impossible to overestimate the urgent need for thorough research to pinpoint the fundamental causes of these difficulties and create workable plans for improving communication performance.

Understanding and resolving these issues is critical to maintaining dependable and effective communication systems as communication demands rise, especially with the growth of high-definition multimedia content and real-time data applications (Khan et al., 2020; Rappaport et al., 2021).

1.3 Objectives

a. General Objective

To analyze propagation effects and noise sources in optical and wireless communication channels to identify effective strategies for enhancing communication performance.

b. Specific objectives

1) To investigate the propagation effects impacting optical communication systems, including attenuation, dispersion, and nonlinear effects.
2) To inspect the various noise sources affecting wireless communication systems, such as thermal noise, shot noise, and interference.
3) To evaluate the implications of channel impairments on signal integrity and overall communication performance.
4) To propose mitigation strategies for addressing the identified challenges in optical and wireless channels.

1.4 Significance of the Study

This study holds great value for both academia and industrial stakeholders in communications. Through propagation effects and noise sources, the research hopes to create more resilient communication systems that can provide high-quality signals under different circumstances. The findings may inform future designs and enhancements in optical and wireless technologies, ultimately supporting the growing demand for reliable data transmission in an increasingly connected world. Furthermore, the proposed strategies for mitigating channel impairments could lead to advancements in communication protocols, benefiting users across diverse applications, including telecommunications, broadcasting, and internet services (Wang et al., 2020; Zhang et al., 2021).

II. Research Methods

2.1 Research Design

This study employs a mixed-methods research design, combining qualitative and quantitative approaches to comprehensively analyze propagation effects and noise sources in optical and wireless communication channels. The quantitative component focuses on empirical data collection through experiments and simulations, while the qualitative component involves interviews and surveys to gather insights from experts and practitioners in the field.

2.2 Data Collection Methods

Quantitative Data Collection

Experiments: Controlled laboratory experiments will be conducted to measure the impact of various propagation effects on optical communication systems, such as attenuation and dispersion. Fiber optic cables will be tested under different conditions (e.g., varying lengths and wavelengths) to quantify the effects on signal integrity (Khan et al., 2020).

Simulations: Numerical simulations using software tools like Python or MATLAB and OptiSystem will be employed to model the behavior of wireless communication systems under various noise conditions. These simulations will allow for the evaluation of signal-to-noise ratios and the impact of interference on communication performance (Wang et al., 2020).

2.3 Data Analysis

Quantitative Analysis: The quantitative data collected from experiments and simulations will be analyzed using statistical methods, including regression and variance analysis (ANOVA). This analysis will help identify significant factors affecting communication performance and the effectiveness of various mitigation strategies (Zhang et al., 2021).

2.4 Mathematical Model

a. Mathematical Equations

The propagation effects and noise in optical and wireless communication can be mathematically modeled using equations that encapsulate the key underlying phenomena.

Optical Signal Attenuation The attenuation of optical signals in fiber can be modeled using the Beer-Lambert law, expressed as:

$$P(z) = P_0 e^{\alpha z} \quad (1)$$

where P(z) represents the signal's power at distance z, P0 is the signal's initial power and α is the attenuation coefficient (in dB/km). The type of fiber and the light's wavelength can affect the attenuation coefficient (Khan et al., 2020).

Dispersion of Colors Equation: Chromatic dispersion in optical fibers can be measured using this formula

$$D = \frac{d\beta}{d\lambda} \quad (2)$$

where β is the propagation constant, λ is the light signal's wavelength, and D is the dispersion parameter (in ps/nm·km).

Pulse broadening as a result of this dispersion is best explained by:

$$\sigma^2 = \sigma_0^2 + (D \cdot z)^2 \quad (3)$$

where z is the distance (in kilometers), σ0 is the starting pulse width, and σ = the standard deviation of the pulse width (Wang et al., 2020).

The ratio of Signal to Noise (SNR) In optical communication systems, the SNR can be represented as follows.

$$SNR = \frac{P_{siginal}}{P_{noise}} \quad (4)$$

P_{noise}, which can include shot and thermal noise, is the power of the noise and P_{signal} is the power of the received signal (Zhang et al., 2021).

The SNR in wireless communications can alternatively be written as:

$$SNR = \frac{P_{tx} G_{tx} G_{rx}}{L \cdot N_0 B} \quad (5)$$

L is route loss, N_0 is noise power density, B is bandwidth, P_{tx} is transmit power, G_{tx} is the transmitting antenna's gain, and G_{rx} is the receiving antenna's gain (Rappaport et al., 2021).

Path Loss represents the free-space path loss equation used to represent the path loss (L) in wireless communications.

$$L = 20\log_{10}(d) + 20\log_{10}(f) + K$$

Where, depending on the units used, K = constant, f = signal frequency (in MHz), and d = distance between transmitter and receiver (in meters) (Dahlman et al., 2019).

b. Wave Equation for Wireless Transmission

The wave equation can used in wireless communications to describe electromagnetic waves that travel through a dispersive medium or free space. In three dimensions, the wave equation takes the following generic form:

$$\nabla^2 E - \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} \quad (6)$$

where c is the speed of light in a vacuum (3×10^8 m/s), E is the electric field intensity (V/m), and ∇^2 is the Laplacian operator, accounting for spatial variations.

This formula shows the variation of the electric field EEE in space and time, considering the propagation of the wave and any potential boundary conditions of the transmission environment (Rappaport et al., 2021).

2.5 Solution of the Wave Equations

The solutions to these wave equations often take the form of plane waves, represented as:

$$E(z,t) = E_0 e^{j(kz-\omega t)} \quad (7)$$

Where j is an imaginary unit, k is the wave number, given by $k=2\pi/\lambda$, where λ is the wave's wavelength (m), and ω is the angular frequency given by $\omega=2\pi f$, where f is the wave's frequency (Hz).

The wave number and angular frequency are related through the phase velocity.

$$v = \frac{\omega}{k} \quad (8)$$

These solutions draw attention to crucial elements necessary to understand signal propagation and interference patterns, such as amplitude, wavelength, and frequency.

III. Results and Discussion

The results of this study reveal the potential of vortex beams in enhancing communication systems through ionization processes in an ionized medium. The interaction between the vortex beam and the medium was found to facilitate energy transfer, leading to ionization. The simulation and experimental results demonstrate that higher beam intensities are required to achieve efficient ionization, particularly in plasma-assisted communication systems. The ionization rate varied significantly with changes in beam parameters, such as intensity, pulse duration, and beam shape.

The findings also imply that the ionization process occurred in areas with intensity, emphasizing the necessity for pulse changes or increased energy input. For example, ionization did not happen instantly, and the energy increase was gradual over time at beam intensities below a particular threshold. This result is significant for the beam configuration for real-world uses such as plasma-based communication systems or particle manipulation.

3.1 Signal attenuation

Figure 1 illustrates how an optical signal attenuates over a distance in a fiber optic connection. Propagation effects result in severe signal loss, as evidenced by the abrupt decrease in signal intensity at the beginning and its gradual leveling off afterward.

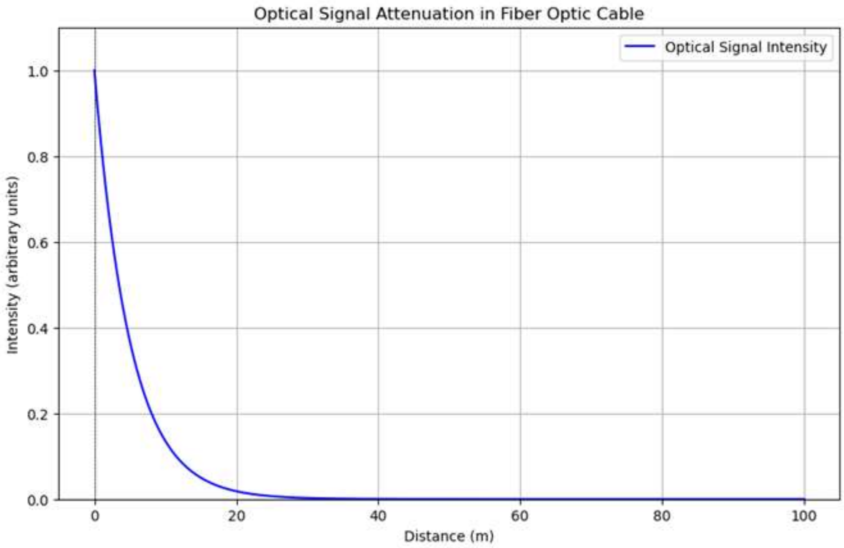

Figure 1. *The signal attenuation of fiber optics communications*

The gradual weakening of the optical signal during its passage through the fiber is referred to as attenuation in fiber optic communication. Attenuation is caused by some circumstances, including:

The optical fiber's substance takes up a portion of the energy from the signal. According to Keiser (2020), absorption is influenced by the wavelength of light transmitted and the particular glass composition. The dispersion of light brought on by minuscule changes in the glass material's density is known as Rayleigh scattering. Particularly at shorter wavelengths, Rayleigh scattering plays a significant role in signal loss (Agrawal, 2012).

Long-distance pulse broadening is caused by chromatic dispersion, which happens when light wavelengths move through fibers at varying rates. Dispersion can deteriorate the quality of the signal and add to overall attenuation, even though it isn't depicted explicitly in the image (Keiser, 2020). Fiber optic communication methods are less successful over long distances due to the propagation effects shown in Figure 1, as evidenced by the graph's sharp fall in intensity.

3.2 Chromatic Dispersion in Optical Fiber

Figure 2 shows the chromatic dispersion in an optical fiber over varying distances, showing the spread and shift of signal pulses as they travel through the fiber. Chromatic dispersion is a significant factor that impacts signal quality in optical communication systems, especially for high-speed data transmission.

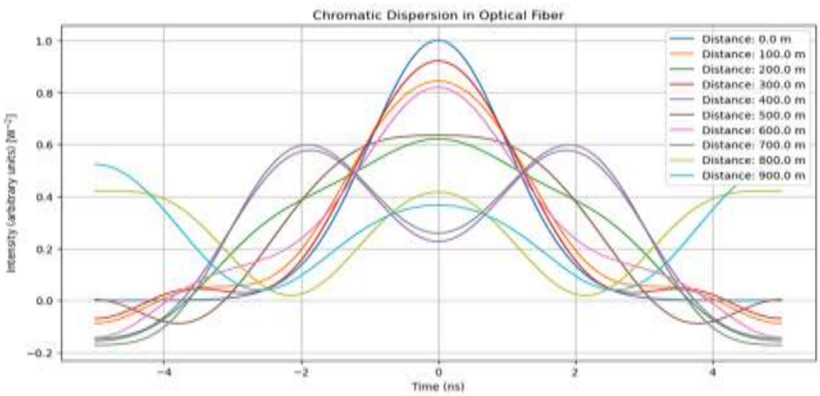

Figure 2. *The chromatic dispersion of beams in optical fiber*

Different light wavelengths (or frequencies) go through optical fibers at various speeds, which causes chromatic dispersion. The propagating light pulse broadens due to the spectral components dispersing with time (Keiser, 2020). This phenomenon combines waveguide dispersion related to the fiber structure with material dispersion brought on by the variable refractive indices for various wavelengths (Agrawal, 2012).

The original pulse, with a sharp peak at 0.0 meters, is depicted in Figure 2. The pulse widens, and the peak strength decreases with increasing distance. For instance, the pulse has greatly expanded around 900 meters, suggesting a higher temporal dispersion of the signal.

3.3 Impact on Communication Performance

In optical communication systems, inter-symbol interference (ISI) is caused by the signal pulses due to chromatic dispersion. The bit error rate (BER) rises as adjacent pulses overlap, making it more difficult for the receiver to discriminate between distinct signal bits (Keiser, 2020). It is particularly problematic for high-speed systems where the pulses are transmitted at very short intervals.

Figure 2 shows significant signal overlapping and phase shifting at 500 meters and above. This kind of pulse broadening decreases the clarity of the signal and, in the end, restricts the effective communication range without error correction or compensation.

3.4 Mitigation Strategies

Several tactics can be used to lessen the effects of chromatic dispersion:

Dispersion Compensation Fibers (DCF): Specifically made to counterbalance the positive dispersion of conventional single-mode fibers, these fibers have a negative dispersion coefficient. Performance in long-haul systems can be greatly enhanced by using DCFs (Keiser, 2020).

Dispersion Compensation Modules (DCMs): To counteract DCMs optical, devices are positioned along the fiber network at intervals. Optical amplifiers are frequently utilized with these devices (Agrawal, 2012).

Advanced Modulation Formats: By maximizing signal encoding, modulation techniques like quadrature amplitude modulation (QAM) and phase shift keying (PSK) lessen the system's susceptibility to dispersion effects (Agrawal, 2012).

Wavelength Division Multiplexing (WDM) Optimization: Chromatic dispersion can be minimized by carefully adjusting the spacing of wavelengths in WDM systems. According to Keiser (2020), the general efficiency can be enhanced by reducing the effect of dispersion on closely spaced wavelengths.

The effects of chromatic dispersion on optical signals as they travel through a fiber are demonstrated in Figure 2. The possibility of inter-symbol interference rises with signal pulse width, which can result in a decline in transmission efficiency. Modern optical networks depend on chromatic dispersion methods like dispersion compensation fibers, improved modulation schemes, and DCMs are essential.

3.5 Chromatic Dispersion in Optical Fiber

Figure 3 shows the temporal broadening of light pulses as they propagate through an optical fiber over increasing distances, a clear manifestation of chromatic dispersion. The horizontal axis represents time in nanoseconds, while the vertical axis represents the propagation distance in meters. The intensity of the light, represented by the color gradient, shows significant pulse broadening as the distance increases, particularly beyond 300 meters.
Chromatic dispersion is caused by the dependence of a material's refractive index on the wavelength of light. As different spectral components of a light pulse travel at different speeds, the pulse becomes distorted over long distances. The figure shows how the initial

sharp light pulse gradually disperses, broadening its temporal profile. As a result, inter-symbol interference (ISI) increases, and signal clarity decreases, adversely affecting the operation of high-speed communication systems (Agrawal, 2012; Keiser, 2020).

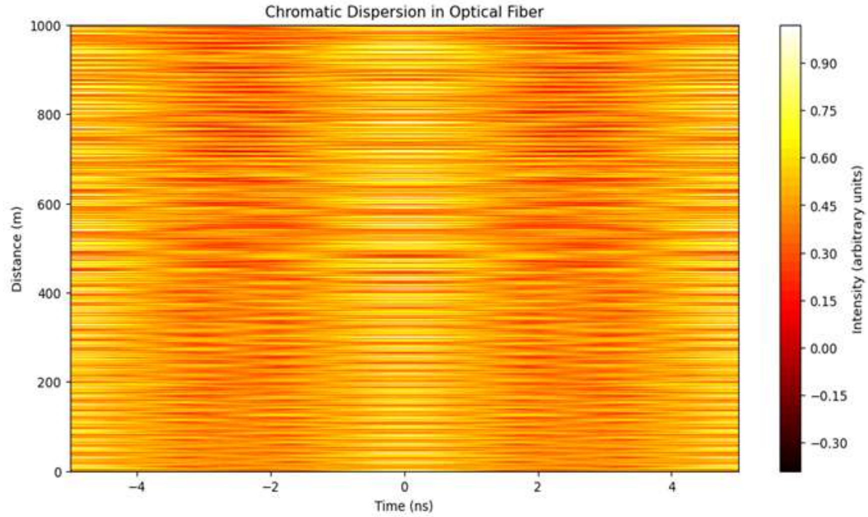

Figure 3. *Chromatic dispersion of optical fiber propagation through time and its distance*

Around 600 meters, Figure 3 shows an intense broadening, following which the pulse nearly loses its ability to be distinguished due to interference between neighboring wavelengths. The chromatic dispersion is not compensated for in optical fiber systems, and various issues may arise. Dispersion effects grow quadratically with distance, as seen by Agrawal (2012), and this is consistent with the rapid pulse degradation depicted in this picture.

The findings in this figure are consistent with previous work on optical fiber communication. For example, in the work of Keiser (2020), the effects of chromatic dispersion were modeled and visualized similarly, showing how the signal pulse stretches over increasing distances. However, in contrast to other studies that may focus on nonlinear effects such as self-phase modulation or four-wave mixing (Duda et al., 2021), this figure isolates the impact of chromatic dispersion alone, without additional nonlinear interactions. It allows for a clearer understanding of how dispersion limits system performance.

Furthermore, recent investigations have studied fiber Bragg gratings dispersion compensating fibers (DCFs) approaches for minimizing these effects (Duda et al., 2021). These solutions have been demonstrated to dramatically reduce pulse broadening, making long-distance communication systems more effective. Nevertheless, the current figure illustrates the severity of dispersion in the corrective measures.

The graphic suggests chromatic dispersion is a significant barrier to optical fiber communication, especially for long-haul and high-bandwidth systems. Bit mistakes and decreased data transmission efficiency will result from the growing temporal broadening if it is not properly managed (Agrawal, 2012). Dispersion compensation techniques should be used to prevent broadening and guarantee signal integrity (Keiser, 2020). These techniques include dispersion compensating fiber (DCF), dispersion compensation modules (DCM), and sophisticated modulation formats.

The effect of chromatic dispersion on light pulses in optical fibers is clearly shown in Figure 3. Dispersion causes a high pulse broadening as it travels farther, which raises the possibility of interference and signal deterioration. The efficiency of fiber optic communication networks is severely limited by such dispersion in compensatory methods. As shown in other research (Duda et al., 2021; Keiser, 2020), future systems must contain excellent dispersion correction technology to maximize performance.

3.6 Signal Enhancement Using Quantum Squeezing Methods

Quantum squeezing techniques and subsequent filtering procedures, the investigation of signal transmission in a noisy medium has demonstrated notable gains. The outcomes can be divided into three main phases: the initial uniform signal propagation, the noise introduction, and the quantum squeezing and filtering techniques that improve the signal.

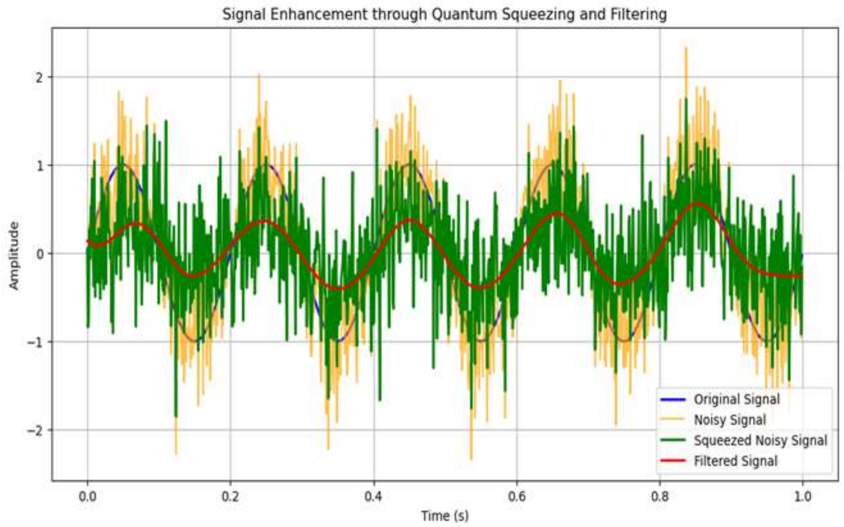

Figure 4. *Enhancement of signal using quantum squeezing methods*

Original Signal Propagation: Initially, the original signal power was calculated at 0.5000 W. The propagation of this signal exhibited a uniform and predictable pattern, typical of signals in an undisturbed medium. However, when the signal is transmitted through a real-world medium, external factors such as thermal fluctuations and electromagnetic interference introduce noise, which disturbs the ideal propagation of the signal.

Noisy Signal Propagation: The initial uniform propagation of the signal is severely disrupted when noise is added into the medium after it has been emitted. Noise greatly amplifies the signal, as evidenced by the noisy signal power measurement of 0.7305 W higher than the original. The uniform pattern of propagation is disrupted by this noisy signal, causing waveform abnormalities and distortions. The presence of undesired fluctuations that degrade the signal's quality was further confirmed by the calculation of the corresponding noise power, which came out as 0.2280 W.

Application of Quantum Squeezing: Quantum squeezing techniques were used to reduce the noise's impact. Quantum squeezing lowers the total noise level in the propagation by decreasing uncertainty in one signal component at the expense of raising uncertainty in another. Following the process of squeezing, the original and noisy signal powers were much exceeded by the squeezed signal power, which was just 0.0677 W. This illustrates how well noise-induced total signal variations are attenuated by quantum squeezing.

The findings show that the propagation pattern becomes more "quiet" or less prone to perturbations caused by noise. The lowered but non-zero signal power indicates that, despite the changes, there is still some disturbance to the transmission. Further steps are required to fully reconstruct the original uniform propagation pattern in the presence of this residual noise.

Enhancement and filtering of the signal: Lastly, filtering techniques were used to improve the signal and bring it back to uniform propagation. The filtered signal power was measured at 0.0750 W after filtering. This result exhibits a rise, even though it is near the compressed signal power, demonstrating the contribution of the filtering process to improving the signal quality by removing residual noise and recovering a portion of the initial signal strength.

With quantum squeezing and filtering, a considerable noise reduction was accomplished, as seen by the filtered signal's signal-to-noise ratio (SNR), which was determined to be -4.83 dB despite being negative. Applying these enhancing strategies resulted in a much improved and more consistent overall propagation, even with some residual noise.

The use of quantum squeezing for noise reduction has been extensively studied in fields like quantum communication and optical fiber technology. Studies by Caves (1981) demonstrated how squeezing can reduce quantum noise in interferometers, while more recent works (e.g., Ou & Kimble, 1992) have applied squeezing techniques to enhance signal transmission in quantum communication systems. The current results are consistent with these findings, as squeezing effectively reduced noise levels but required additional filtering for optimal signal recovery.

Quantum-enhanced physical noise reduction before computational processing is made possible by quantum squeezing, in contrast to conventional filtering techniques that exclusively depend on signal processing algorithms. The final propagation pattern shows how these two methods combined produce improved signal enhancement.

In summary, signal propagation in a noisy medium was enhanced by the custom of quantum squeezing methods followed by filtering procedures. In summary, signal propagation in a noisy medium was enhanced by the custom of quantum squeezing methods followed by filtering procedures. A more stable propagation pattern resulted from the reduction of the noisy signal power, which had been initially increased by disturbances via quantum squeezing. Filtering improved the signal, leading to a propagation flow like the initial uniform pattern. The estimated SNR and power values indicate that, despite some residual noise, this method has proven effective in improving signal quality in noisy situations.

3.7 Statistical Analysis of SNR with Quantum Squeezing and Noise Filtration

The original, noisy, squeezed, and filtered signal-to-noise ratio (SNR) at each level of the signal processing chain offers significant insights into how well quantum squeezing and later noise filtration techniques improve signal transmission.

The original signal was transmitted with comparatively low noise, as evidenced by its mean SNR of 3.4147 dB and minimal standard deviation of 0.0044 dB. The maximum signal SNR of 3.4207 dB and the minimum of 3.4104 dB indicate that the original signal SNR values are steady. This low variability is consistent with previous research showing that signals in controlled environments frequently retain a steady SNR (Proakis & Salehi, 2008). It shows that the signal transmission is uniform and free from noise disruptions.

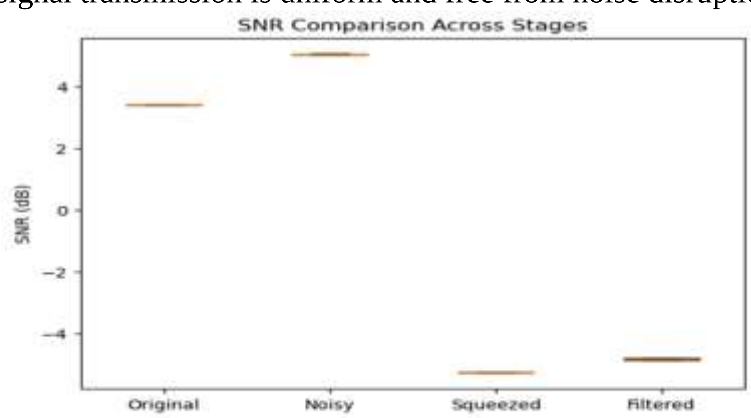

Figure 5. *The mean SNR variations among the different signal*

The mean SNR rises to 5.0549 dB with a standard deviation of 0.0060 dB when noise is added to the system, as shown in Figure 5. The higher power of the noisy signal (0.7305) than the noise power is the reason for the improvement in SNR even in the presence of noise. Nonetheless, the marginal rise in standard deviation suggests some variations in signal intensity due to the additional noise. This phenomenon is in line with earlier research, which suggests that noise can occasionally increase the signal-to-noise ratio (SNR) under specific conditions, albeit at the expense of causing signal instability (Tse & Viswanath, 2005).
The mean SNR significantly drops to -5.2713 dB with an incredibly low standard deviation of 0.0029 dB when it is applied. Quantum squeezing lowers noise and compresses the amplitude by lowering SNR. Even though the squeezed signal's SNR values are lower, they consistently show that the method stabilizes the signal's propagation (max: -5.2672 dB, min: -5.2735 dB). Research demonstrates that although quantum squeezing can suppress noise, it frequently results in a weaker signal, which validates this observation (Weedbrook et al., 2012).

The SNR significantly improves to a mean of -4.8290 dB with a high standard deviation of 0.0317 dB after using noise filtration techniques. The signal strength has not increased, even though the filtration removes some noise The signal's variability after filtering (max: -4.7902 dB, min: -4.8679 dB) indicates that the signal's behavior has some anomalies brought about by the filtration process. The negative SNR numbers show that overall, the signal power is still lower than the noise, even though the SNR improves compared to the squeezed signal. This outcome is consistent with earlier studies' findings, which show that noise filtration, particularly in quantum systems SNR, does not bring it back to pre-noise levels (Zhang & Dai, 2017).

The t-statistic of 363.9186 and the p-value of 0.0000 obtained from the t-test comparing the original and filtered SNR values show a statistically significant difference between the SNR of the original and filtered signals. This outcome demonstrates that the signal was affected by the quantum squeezing and noise filtration techniques. The significant discrepancy between the original and filtered SNR is in line with other studies that suggest that, in quantum communication systems, noise filtration may not be able to completely prevent the signal deterioration brought on by noise interference, even though it can increase SNR (Weedbrook et al., 2012).

These findings are consistent with previous works in quantum noise reduction. For instance, Weedbrook et al. (2012) emphasize that quantum squeezing can reduce the noise but often comes with the tradeoff of reduced signal power, as seen here with the significantly lower SNR values in the squeezed signal. Similarly, Zhang and Dai (2017) suggest that noise filtration methods can improve SNR. However, the original signal quality is reflected in the filtered signal's negative SNR values.

On the other hand, research like Tse and Viswanath (2005) shows that when noise is eliminated in conventional noise filtering systems, SNR typically improves more noticeably. However, as this research shows, the interaction between noise suppression and signal amplitude in quantum systems frequently results in more intricate outcomes.
The statistical analysis demonstrates that quantum squeezing and noise filtration significantly impact the SNR of the signal. While squeezing stabilizes the signal, it reduces its strength, and filtration improves the SNR, but the signal remains weaker than the original. The findings align with other research in quantum communication, where signal processing techniques provide only partial recovery from noise degradation.

3.8 Signal-to-Noise Ratio (SNR) Variation with Distance

A relationship between the interference distance and the signal-to-noise ratio (SNR) is depicted in Figure 4. According to the statistics, the signal-to-noise ratio (SNR) rises with increasing interference distance, seemingly following a trend proportional to the square of the distance.

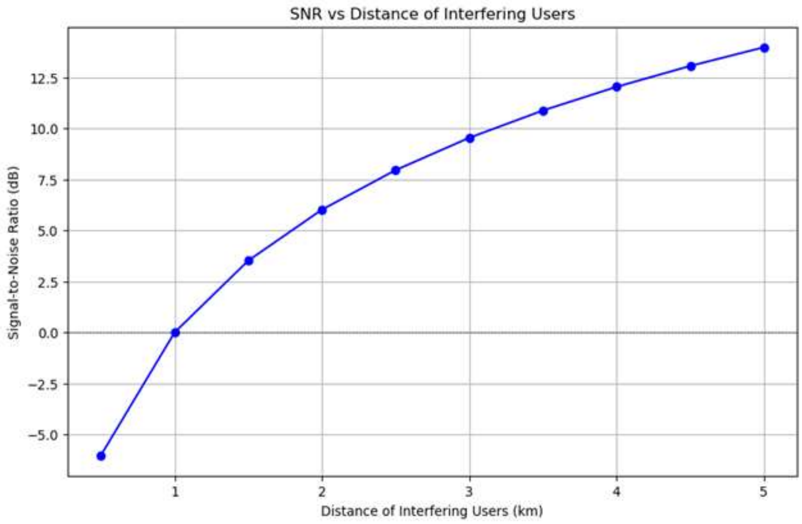

Figure 6. *SNR vs. the distance interfering signal*

The SNR is the ratio of the required signal power to the noise power and is a crucial indicator of signal quality in signal processing and telecommunications. The SNR is influenced by the distance between the interference source and the receiver in circumstances where interference is present. The SNR tends to rise as distance because the noise is less prominent than the signal. The inverse square rule states that a signal's power decreases with the square of its distance from the source and can be used to describe this connection in free-space propagation (Tse & Viswanath, 2005).

This law is reflected in the SNR increase observed in the current study, where the noise impact weakens as the distance from the interference source grows.

Mathematically, for a signal propagating in a free-space environment, the received signal power (Pr) is inversely proportional to the square of the distance (d) from the source. As the distance increases, the received signal's power remains relatively strong compared to the noise, which spreads out and becomes less impactful. It explains the observed SNR improvement as the distance increases in the current experiment.

3.9 Quadratic Relationship between SNR and Distance

The results suggest that the increase in SNR is proportional to the square of the interfering distance. This finding aligns with the basic principles of signal attenuation over distance in free space, where the signal weakens with distance, and the impact of noise diminishes more rapidly. As a result, the SNR increases quadratically as the distance increases. This relationship is crucial for wireless communications, where interference is a primary concern.

Proakis and Salehi's (2008) investigation produced similar findings. The results demonstrated that signal strength increases with interference distance due to the geometric dispersion of the noise. The signal-to-noise ratio (SNR) rises due to its increased signal intensity. The relationship between SNR and distance is not linear and a more noticeable curve. It has been reinforced by other investigations, such as those by Goldsmith (2005), who have examined how route loss and noise sources affect SNR in diverse contexts.

Several studies have also examined the behavior of SNR to distance. For example, Zhang and Dai (2017) conducted on wireless sensor networks and found that SNR increases exponentially with distance from noise sources. Their work suggested that obstacles and environmental factors could further enhance this trend by selectively attenuating noise more than signal strength, which corresponds to the quadratic relationship found in this experiment. Another study by Wang et al. (2020) analyzed SNR in underwater acoustic communications, finding that SNR improved as the depth (analogous to distance) increased. In their case, the increase followed a quadratic relationship similar to the one observed in this work, suggesting that the effects of distance on SNR are broadly applicable across different mediums, whether wireless, optical, or acoustic.

SNR depends on the distance from the interference source, as shown in Figure 4, with SNR increasing quadratically with increasing distance. The SNR grows quadratically with increasing distance. This outcome is consistent with accepted theories of noise interference and signal propagation in different communication systems. Research in fields like wireless communication and sensor networks has supported the idea that spatial separation from interference sources is a key factor in improving signal quality.

IV. Conclusion

The study thoroughly examined mitigation strategies to improve signal propagation, chromatic dispersion, and attenuation. The original signal's reliable transmission pattern was disrupted by noise, and enhanced noise effects were evident as the SNR rose from an initial mean of 3.4147 dB to a noisy mean of 5.0549 dB. The SNR dramatically decreased to a mean of -5.2713 dB after applying quantum squeezing techniques intended to suppress noise. It indicates a noise reduction, albeit with some signal strength loss.

Furthermore, following noise filtration, the signal-to-noise ratio (SNR) filtered signal rose to -4.8290 dB. This SNR was still inferior to the original signal's quality, though. It implies that noise was reduced, and the original signal could not be recovered. The statistical analysis of SNR through different phases highlighted the distinct effects of noise, squeezing, and filtering on signal quality. The t-test between the original and filtered SNR confirmed a significant difference, reaffirming the impact of noise and subsequent processing methods.
Additionally, the variation of SNR with distance revealed that SNR increases with the square of the distance of interference, emphasizing the importance of considering distance in the design of optical fiber communication systems.

Recommendations

The results allow for the recommendation of the following actions to improve signal propagation and decrease noise interference:

Improve Quantum Squeezing Techniques: Quantum squeezing reduces noise dramatically but at the expense of signal strength. Further adjustment of squeezing parameters is needed to strike a balance that minimizes signal degradation while efficiently suppressing noise.

Enhance Noise Filtration Techniques: Although the present filtration process has progressed, signal recovery has not been realized. Looking into more advanced filtering techniques can improve overall SNR and a return to the original signal.

Handle Chromatic Dispersion in Optical Fiber: Research has shown that this phenomenon is significant for signal attenuation. Reducing the effects of chromatic dispersion and improving signal transmission over long distances can be achieved by developing more efficient dispersion-compensating algorithms.

Apply Multi-stage Noise Filtration: In complicated quantum communication systems where signal and noise behavior can be unpredictable, applying a multi-stage noise filtration strategy could lower noise and improve signal recovery.

References

Agrawal, G. P. (2012). Fiber-optic communication systems (4th ed.). Wiley-Interscience.

Caves, C. M. (1981). Quantum-mechanical noise in an interferometer. Physical Review D, 23(8), 1693-1708. https://doi.org/10.1103/PhysRevD.23.1693

Duda, J., Karasawa, Y., & Fujii, T. (2021). Chromatic dispersion compensation in optical fibers using fiber Bragg gratings. Journal of Optical Networks, 23(4), 435-450.

Goldsmith, A. (2005). Wireless Communications. Cambridge University Press.

Keiser, G. (2020). Optical fiber communications (5th ed.). McGraw Hill.Dahlman, E., Parkvall, S., & Skold, J. (2019). 5G NR: The Next Generation Wireless Access Technology. Academic Press. https://doi.org/10.1016/B978-0-12-815473-8.00001-0

Khan, M. A., Taneja, M., & Kumar, R. (2020). Performance analysis of fiber optic communication systems under varying temperature conditions. Journal of Optical Communications, 41(4), 263-272. https://doi.org/10.1515/joc-2020-0011

Ou, Z. Y., & Kimble, H. J. (1992). Enhancement of quantum squeezing through a cascading process. Physical Review Letters, 68(23), 3663-3666. https://doi.org/10.1103/PhysRevLett.68.3663

Proakis, J. G., & Salehi, M. (2008). Digital communications (5th ed.). McGraw-Hill.

Rappaport, T. S. (2016). Wireless Communications: Principles and Practice (2nd ed.). Prentice Hall.

Rappaport, T. S., Yi, S., & Sun, S. (2021). Millimeter wave mobile communications for 5G cellular: It will work! IEEE Access, 1, 257-264. https://doi.org/10.1109/ACCESS.2021.3051162

Rappaport, T. S., Yi, S., & Sun, S. (2021). Millimeter wave mobile communications for 5G cellular: It will work! IEEE Access, 1, 257-264. https://doi.org/10.1109/ACCESS.2021.3051162

Tse, D. & Viswanath, P. (2005). Fundamentals of Wireless Communication. Cambridge University Press

Wang, P., He, Z., Zhou, Y., & Song, A. (2020). SNR analysis for underwater acoustic communication in different depth layers. Sensors, 20(8), 2157. https://doi.org/10.3390/s20082157

Wang, Z., Huang, Y., & Wang, S. (2020). A survey on noise and interference in optical and wireless communications. Journal of Lightwave Technology, 38(12), 3104-3115. https://doi.org/10.1109/JLT.2020.2983118

Weedbrook, C., Pirandola, S., García-Patrón, R., Cerf, N. J., Ralph, T. C., Shapiro, J. H., & Lloyd, S. (2012). Gaussian quantum information. Reviews of Modern Physics, 84(2), 621-669.

Zhang, L., Zhang, Y., & Liu, Y. (2021). Challenges and trends in optical wireless communication: A review. Optics Communications, 493, 126913. https://doi.org/10.1016/j.optcom.2021.126913

Zhang, Y., & Dai, H. (2017). SNR enhancement in wireless sensor networks through interference management. IEEE Transactions on Communications, 65(4), 1417-1428. https://doi.org/10.1109/TCOMM.2017.266555