Noise shaping technology based on FIR filters

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Abstract. Traditional signal enhancement techniques, such as oversampling, face limitations due to their increased computational complexity and power consumption. As the demand for higher data rates and quality continues to grow, noise shaping techniques become crucial for improving the signal-to-noise ratio (SNR) without exacerbating these constraints. This paper establishes a co-simulation between Virtual Photonics Incorporated (VPI) and MATLAB to create a comprehensive Intensity Modulation Direct Detection (IM/DD) system using simulation tools. The study implements noise shaping techniques based on Finite Impulse Response (FIR) filters to mitigate the impact of quantization noise arising from low-bit Digital-to-Analog Converters (DACs) in the signal generation process, conducting system-level simulations to validate the reliability of the algorithm. In the MATLAB simulations, under Additive White Gaussian Noise (AWGN) channel conditions, the FIR-based noise shaping technique demonstrates a significant improvement in the Bit Error Rate (BER). The joint simulation with MATLAB and VPI shows that noise has been effectively shifted to higher frequency bands, achieving successful noise shaping.

Keywords: Noise shaping, FIR filter, Co-simulation, IM/DD system, Bit Error Rate

1 Introduction

In the era of the digital revolution, the demand for higher data rates and quality amidst constraints like bandwidth and power has intensified. Traditional signal enhancement techniques, such as oversampling, face limitations due to their increased computational complexity and power consumption. Noise shaping technology, pivotal for improving signal-to-noise ratio (SNR) without enlarging these constraints, emerges as a significant innovation, especially when optimized to function effectively without oversampling [1]. This breakthrough in noise shaping optimization marks a transformative approach in digital signal processing, offering substantial benefits across digital audio, telecommunications, and IoT applications. It aligns with the pressing need for efficient, high-quality digital systems capable of operating under stringent conditions, thus paving the way for advancements in ultra-reliable communication and high-fidelity audiovisual experiences. This development signals a

Y. Yue (ed.), *Proceedings of the 2024 International Conference on Mechanics, Electronics Engineering and Automation (ICMEEA 2024)*, Advances in Engineering Research 240,
https://doi.org/10.2991/978-94-6463-518-8_22

shift towards optimizing digital technologies for greater efficiency and performance in the modern digital landscape. This document delineates the development of an enhanced technique capable of shaping quantization noise and clipping distortion within DMT transmitters, without the necessity for oversampling. Analogous to conventional quantization noise shaping techniques utilized in data conversion, the system implemented herein relies on the TR (Tone Reservation) bands that do not carry data. However, diverging from traditional quantization noise shapers, the bandwidth of these TR bands does not necessitate exceeding that of the bands carrying data.

This article commences with an in-depth exploration in the “Theoretical Foundations” section, where it delineates the theoretical principles that underpin the noise shaping technology applied to Finite Impulse Response (FIR) filters. Included within this discussion is an extensive examination of Orthogonal Frequency Division Multiplexing (OFDM) technology alongside its noise shaping methodologies. The narrative further extends to elucidate the differences and similarities among OFDM, Discrete Multi-Tone (DMT), and Intensity-Modulated Direct Detection (IM-DD) systems, detailing the generation process of OFDM symbols and the key technologies that are fundamental to the operational success of OFDM systems. The subsequent third section is dedicated to the execution of a joint simulation employing MATLAB and VPI for the FIR filter’s noise shaping technology, wherein the simulation outcomes are presented and subjected to analytical scrutiny. The concluding fourth section encapsulates the aforementioned simulation results and analytical observations, accentuating the simulation’s limitations while proffering prospective avenues for enhancements in future endeavors.

2 Theoretical Foundations

2.1 Orthogonal Frequency Division Multiplexing Technology

2.1.1 Similarities and Differences between OFDM, DMT, and IM-DD Systems

Orthogonal Frequency Division Multiplexing (OFDM) is a form of Multi-Carrier Modulation (MCM) that facilitates the simultaneous transmission of high-speed serial data by employing frequency division multiplexing. This technique is known for its resilience against multipath fading and its ability to accommodate multiple users. Originating from Multi-Carrier Modulation (MCM), OFDM represents a prominent variant of multi-carrier transmission methods. Its modulation and demodulation processes rely on Inverse Fast Fourier Transform (IFFT) and Fast Fourier Transform (FFT) techniques, respectively, rendering it the simplest and most prevalent approach among multi-carrier transmission strategies.

Discrete Multitone Modulation (DMT) is a multi-carrier modulation technique formed by aggregating multiple non-interfering subcarriers of different frequencies, with the flexibility to employ various modulation formats for the subcarriers. With the rapid development of communication technologies and increasing demands for data transmission capacity, DMT, known for its efficient spectral utilization and strong resistance to inter-channel interference, has been widely applied in high-capacity, short-distance transmission systems [2].

Intensity Modulation with Direct Detection (IM-DD) involves directly envelope detecting the intensity-modulated optical carrier wireless signal, meaning that the intensity-modulated signal can be directly recovered through a photodetector. This system modulates the intensity of the optical carrier wave at the transmitter and directly detects the light signal at the receiver end of a fiber optic communication system.

DMT signals, being real-valued multi-carrier modulation signals, employ Inverse Fast Fourier Transform (IFFT) and Fast Fourier Transform (FFT) for modulation and demodulation, respectively. They are a special type of Orthogonal Frequency Division Multiplexing (OFDM) signal. The primary distinction is that DMT signals require Hermitian symmetry in the frequency domain before IFFT modulation, ensuring that the time-domain symbols obtained through IFFT are real numbers.

In summary, both OFDM and DMT are multi-carrier modulation technologies, generating OFDM and DMT signals, respectively, with DMT signals being a special type of OFDM signal. The baseband signal of DMT is a real-valued signal, requiring only amplitude modulation, whereas the baseband signal of OFDM is a complex signal, necessitating IQ modulation. Since DMT signals are purely real-valued, they can serve as modulation methods in IM-DD systems, compatible with IM-DD systems [3].

2.1.2 Generation Process of OFDM Symbols.

The principle of OFDM involves converting a high-speed digital signal stream into N low-speed data streams. Each of these streams is modulated in its frequency band, with the modulation carriers of the sub-signals being orthogonal to each other. These sub-carriers, carrying digital information, are then superimposed on each other to form an OFDM symbol. The basic process of generating an OFDM symbol is illustrated in Figure 1. Firstly, the input digital signal source is converted from serial to parallel into symbols. These symbols are then mapped, i.e., modulated, from the time domain to the frequency domain.

In this context, Quadrature Amplitude Modulation (QAM) serves as an example to illustrate the concept. The block diagram of an OFDM system is shown in figure 1.

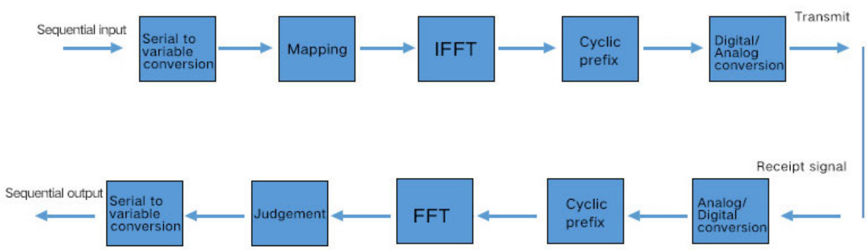

Fig. 1. Block diagram of an OFDM system (Photo/Picture credit: Original)

Quadrature Amplitude Modulation (QAM) is a modulation method in which both phase and amplitude vary simultaneously. It is composed of two independent carriers of the same frequency, with their phases differing by 90 degrees, making them orthogonal to each other [4]. Hence, it is named Quadrature Amplitude Modulation. The mathematical representation of Quadrature Amplitude Modulation is expressed as Equation (1):

$$s(t) = a\sin(\varphi - 2\pi ft) \tag{1}$$

In this article, (t) stands for time, (f) stands for frequency, and (φ) stands for phase. It can be observed that the carrier's amplitude and phase both carry information, which is expanded into Equation (2):

$$s(t) = a\sin(\varphi)\cos(2\pi ft) - a\cos(\varphi)\sin(2\pi ft) \tag{2}$$

Therefore, it can be seen that within the two mutually orthogonal carriers, cos (2πft) and sin(2πft), modulation occurs through the amplitudes asin (φ) and cos (φ) respectively. Let us denote A=asin (φ), B=acos (φ). Hence, this set of amplitudes can be regarded as a vector point (A, B). Thus, Quadrature Amplitude Modulation can be viewed as mapping multiple digital bits to a point on the complex plane, also known as constellation mapping. The vector point is represented by the complex number (S) as shown in Equation (3), and further derived by Euler's formula as shown in Equation (4).

$$S = A + Bj \tag{3}$$

$$s(t) = \mathrm{Re}\left(S\,\square\exp^{j2\pi ft}\right) \tag{4}$$

Up to this point, the signal described is derived from a single digital signal modulated by QAM. An OFDM signal, however, is composed of the superposition of (N) such signals, with the requirement that the carriers of these (N) signals are mutually orthogonal. Assuming the carrier frequency of the first signal is 0 and the second carrier's frequency is (f0), to ensure orthogonality among the sub-carriers and maximize spectral resource utilization, the carrier frequencies of these (N) signals are respectively given by (0， f0， 2f0， …(N - 1) f0). The superposition of these (N) signals is then formed as expressed in Equation (5):

$$x(t) = \mathrm{Re}\left(\sum_{k=0}^{N-1} S_k \exp^{jtk2\pi f_0}\right) \tag{5}$$

$$x(n) = \mathrm{Re}\left(\sum_{k=0}^{N-1} S_k \exp^{jnk\frac{2\pi}{T_0}}\right) \tag{6}$$

It is understood that the formula for the Inverse Discrete Fourier Transform (IDFT) is presented in Equation (7):

$$x(t) = \frac{1}{N}\left(\sum_{k=0}^{N-1} X(k) exp^{jnk\frac{2\pi}{N}}\right) \tag{7}$$

A comparison between the two formulas reveals a notable similarity. This suggests that by applying the Inverse Discrete Fourier Transform (IDFT) to the (N) constellation points mapped by QAM, it becomes possible to achieve the superposition of (N) digitally modulated QAM signals. This finding is of significant importance for the advancement of OFDM technology. Prior to this discovery, the generation of an OFDM symbol involved the modulation of (N) individual signals followed by the summation of the modulated outputs. This process is depicted in the block diagram presented in Figure 2.

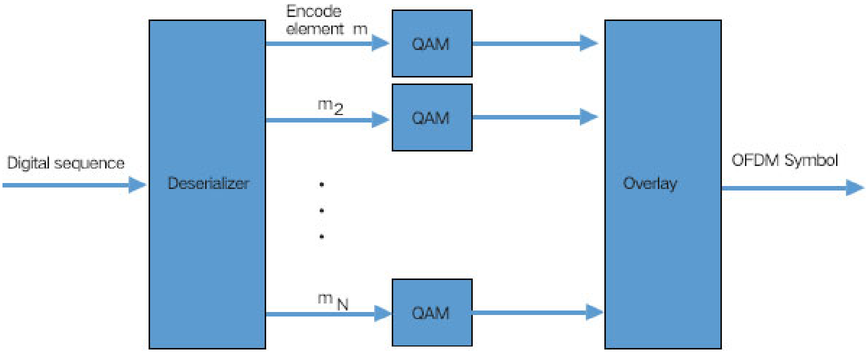

Fig. 2. Overlay diagram of QAM modulation (Photo/Picture credit: Original)

This necessitated that an OFDM system undergo (N) modulation processes to generate a single OFDM symbol, which increased system complexity and resulted in low system efficiency. However, utilizing the Inverse Discrete Fourier Transform (IDFT), as shown in the block diagram in Figure 3, it is possible to replace (N) instances of QAM modulation with a single IDFT operation. This significantly reduces system complexity and enhances communication efficiency. In addition, the evolution of digital signal processing technology has led to the adoption of the Fast Fourier Transform (FFT) over the Discrete Fourier Transform, resulting in enhanced efficiency and decreased complexity of the OFDM system [5].

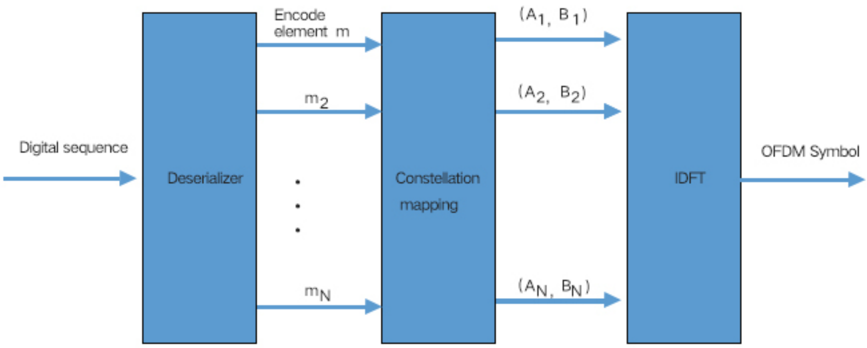

Fig. 3. Overlay diagram of QAM-IDFT modulation (Photo/Picture credit: Original)

2.1.3 Key Technologies in Orthogonal Frequency Division Multiplexing Systems

The previous section introduced the process of generating Orthogonal Frequency Division Multiplexing (OFDM) symbols, with Quadrature Amplitude Modulation (QAM) serving as an example. This section will discuss several key technologies in OFDM systems. As depicted in Figure 1, following the generation of an OFDM symbol, a cyclic prefix is added. The technical principle of the cyclic prefix will be elucidated in this section. After the addition of the cyclic prefix, the signal at the transmitter is converted from digital to analog, and at the receiver, it is converted from analog to digital. The digital-to-analog and analog-to-digital conversions will also be addressed.

Cyclic Prefix Technology: *Between two OFDM symbols, the delay spread of t*he carrier from the previous symbol can cause interference to the carrier of the next symbol. This interference phenomenon is known as Intersymbol Interference (ISI), also referred to as inter-carrier crosstalk. Traditionally, to prevent inter-carrier crosstalk, a guard interval (GI) is inserted between two symbols. This involves reserving a period of idle interval between symbols, with the interval's duration exceeding the signal's maximum delay. This ensures that even if there is a delay in the carrier of the previous symbol, it will not interfere with the next symbol. However, in OFDM communication systems, the multipath effect exists. Multipath effect refers to the presence of multiple signal transmission paths between the transmitter and receiver, with signals experiencing different delays and fading when traveling through different paths. At the receiver, these differences may be amplified. Therefore, merely adding an idle interval as a guard interval might still be susceptible to inter-carrier crosstalk, reducing the orthogonality between sub-carriers [6].

The chosen method involves copying a certain proportion of the tail signal of the OFDM symbol to the front as a protective interval. This method is known as adding a cyclic prefix. By adding a cyclic prefix, the sum of the signal delays caused by sub-carriers and multipath always equals zero. This maintains the orthogonality between the sub-carriers. At the receiver, when restoring the signal with FFT, it is only necessary to remove the cyclic prefix.

Digital−to−Analog/Analog−to−Digital Conversion Technology: At the OFDM transmitter, the output signal from the IFFT is digital. To convert this signal into an analog signal, a digital-to-analog converter is required. Therefore, the performance of the digital-to-analog conversion determines the quality of OFDM communication [7].

2.2 Noise Shaping

This section illustrates the enhancement of the Signal-to-Noise Ratio (SNR) of DMT signals post digital-to-analog conversion through the application of pitch preservation and noise shaping techniques. Noise shaping is frequently applied in data conversion using low-resolution quantizers (often 1-bit quantizers) to achieve effective high resolution; such data converters are known as Delta-Sigma (Δ−Σ) or Sigma-Delta (Σ−Δ) converters. However, traditional (Δ−Σ) converters necessitate a high oversampling rate for noise shaping. The feasibility of noise shaping without oversampling is demonstrate.

The implemented noise shaping system, as depicted in Figure 4(a), involves X(ejω) which represents the digital input slated for processing and conversion to an analog signal. (Q) symbolizes a simulated DAC, primarily utilized for quantization noise acquisition, where quantization noise refers to the discrepancy between data before and after DAC processing. $H(e^{j\omega})$ signifies the channel response of the feedback filter. From Figure 4(a), the structure for noise shaping is derived [8].

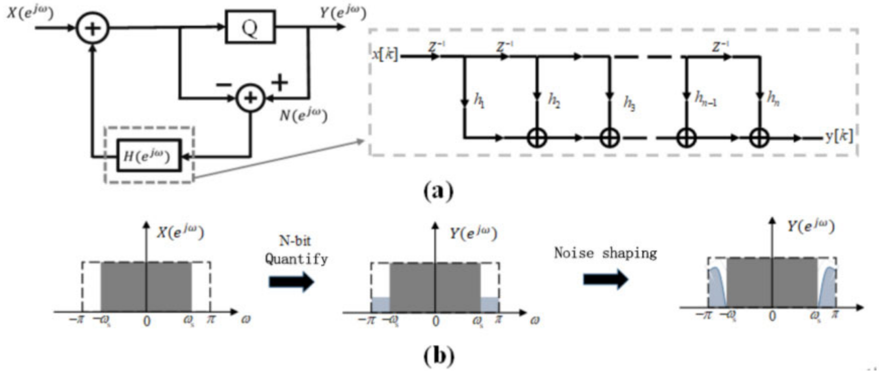

Fig. 4. (a) Structure based on FIR noise shaping technology (b) Principle of operation in the frequency domain [8]

The output Y ($e^{j\omega}$) can be represented by Equation (8):

$$Y(e^{jw}) = X(e^{jw}) + (1 + H(e^{jw}))N(e^{jw}) \tag{8}$$

To minimize quantization noise within the signal bandwidth, it is essential for the quantization noise post the noise shaping technique output to be less than the quantization noise prior to this process. The optimization problem can be mathematically formulated as Equation (9) based on the provided documentation:

$$\begin{cases} \min \lVert 1 + Eh \rVert \\ h \end{cases} \tag{9}$$

In the above equation,

$$E = \begin{pmatrix} e^{-j\omega_1} & e^{-j2\omega_1} & \cdots & e^{-jn\omega_1} \\ e^{-j\omega_2} & e^{-j2\omega_2} & \cdots & e^{-jn\omega_1} \\ \vdots & \vdots & \ddots & \vdots \\ e^{-j\omega_s} & e^{-j2\omega_s} & \cdots & e^{-jn\omega_s} \end{pmatrix}, h = \begin{pmatrix} h_1 \\ h_2 \\ \vdots \\ h_n \end{pmatrix} \tag{10}$$

The matrix (E) encompasses frequencies (ω1, ω2 ,..., ωs) that carry information. In a typical DMT system, due to high-frequency attenuation and aliasing, the high-frequency sub-carriers often exhibit a lower Signal-to-Noise Ratio (SNR). Considering the lower SNR of high-frequency sub-carriers, these information-carrying frequencies occupy the lower frequency bands, with a bandwidth of (B_s).

Since the aforementioned strategy only constrains noise within the signal band, it might result in the noise within the signal band still being substantial. Therefore, to further minimize the impact of quantization noise within the signal bandwidth, the introduction of a weighting matrix is necessary [9].

$$W = diag\left(W_1, W_2, \cdots, W_P, W_{P+1}, \cdots W_{P+Q}\right) \tag{11}$$

To minimize Equation (2.2) and achieve joint constraints both within and outside the signal band, (W1-WP) and (WP+1-WP+Q) respectively represent the weights for the signal frequency band and the unused frequency segments.

With the introduction of the weighting matrix, the optimization problem is transformed into Equation (11):

$$\begin{cases} \min \square 1 + Eh \square \\ \quad h \end{cases} \tag{12}$$

In the above equation,

$$A = \begin{pmatrix} e^{-j\omega_1} & e^{-j2\omega_1} & \cdots & e^{-jM\omega_1} \\ e^{-j\omega_2} & e^{-j2\omega_2} & \cdots & e^{-jM\omega_1} \\ \vdots & \vdots & \ddots & \vdots \\ e^{-j\omega_{P+Q}} & e^{-j2\omega_{P+Q}} & \cdots & e^{-jM\omega_{P+Q}} \end{pmatrix} \tag{13}$$

The optimal coefficients (h) of the solution are as follows:

$$h_{opt} = -\begin{pmatrix} WA_r \\ WA_i \end{pmatrix} \dagger \begin{pmatrix} W \\ O \end{pmatrix} \tag{14}$$

where(†) denotes the pseudoinverse of the matrix.

The principle of operation for FIR noise shaping technology involves the use of an FIR filter to filter the quantization noise. This redistributes the majority of the quantization noise outside the signal band, leaving only a minimal amount within the signal band, as illustrated in Figure 4(b). Figure 4(b) presents the spectral diagrams for the input signal, the quantized output without noise shaping technology, and the quantized output with noise shaping technology, respectively [10].

3 Modeling and Simulation

For this simulation, a complete 25GHz bandwidth 16QAM-DMT (Discrete Multitone Transmission) system is constructed, with the DAC (Digital-to-Analog Converter) sampling rate and quantization bit depth set to 80Gsa/s and 4/5-bit, respectively. The task includes writing comprehensive code for both the transmitter and receiver (including DMT signal modulation/demodulation, based on FIR noise shaping technology), and conducting simulation tests for Bit Error Rate (BER) and Received Optical Power (ROP) curves. The simulation system is constructed using two software tools: MATLAB for signal processing and VPI for providing an optical channel.

3.1 MATLAB Project

The structure of the Matlab code is shown in Figure 5, with the functions of each file as follows.

First, the read_configuration.m script reads the relevant configuration parameters de-fined in the configuration.json file. These parameters provide the necessary configura-tions for the entire simulation process, including modulation / demodulation methods, filter design parameters, etc.

Next, the qam16_dmt_mod.m function modulates the input bit sequence using 16-QAM modulation, followed by further modulation using DMT (Discrete Multitone Modulation) techniques. This step generates the modulated signal ready for transmission.

After signal transmission, the qam16_dmt_demod.m function first demodulates the received signal using DMT demodulation, followed by 16-QAM demodulation to recover the original bit sequence.

For the design of the FIR filter and the implementation of noise shaping, the generate_E.m script generates the matrix ArAiT based on the number of in-band frequency samples and the number of FIR taps. This matrix is used for subsequent filter design.

The get_opt_fir.m function uses the weighting coefficients Ws and the frequency partitioning matrix ArAiT to calculate the optimal FIR filter tap coefficients vector h. The goal is to design an FIR filter with optimal performance under given conditions for effective noise shaping.

The quantize_n_bits.m script quantizes the signal to n bits and applies noise shaping technology simultaneously to improve the signal-to-noise ratio during the quantization process.

ofdm_tx.m and ofdm_rx.m simulate the OFDM system's transmitter and receiver, respectively. The transmitter is responsible for generating and sending the OFDM signal, while the receiver processes the received signal and attempts to recover the original data sent from the transmitter.

Finally, the main.m script acts as the main entry point for the simulation, invoking all the aforementioned functions and scripts to perform a complete system test. It simu-lates the entire communication process, from signal generation and modulation to transmission, reception, demodulation, and ultimately evaluates the system's performance indicators, such as Bit Error Rate (BER) and the quality of the received signal.

3.2 VPI Project

Building an optical communication system using VPI, as shown in Figure 5.

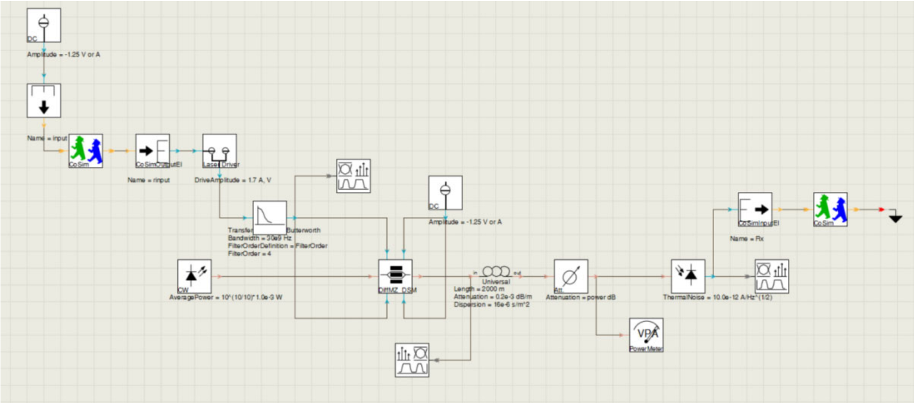

Fig. 5. VPI System (Photo/Picture credit: Original)

In the VPI environment in figure 5, a complete optical communication system is designed, including the selection of suitable optical components such as light sources, modulators, optical fibers, amplifiers, and receivers, and configuring their parameters to reflect real-world application scenarios.

The characteristics of the optical channel, such as the dispersion and nonlinear effects of the optical fibers and the gain and noise characteristics of optical fiber amplifiers, are simulated using models provided by VPI. This step is crucial for assessing the performance degradation of the signal during fiber transmission.

Through the interface between VPI and MATLAB (API or file exchange), signals generated and processed in MATLAB are imported into VPI for simulation of optical channel transmission. For example, signals in specific formats (such as 16 QAM-DMT signals processed with FIR filter noise shaping technology) can be generated in Matlab and then imported into VPI for optical channel simulation.

Simulations are run in VPI, simulating the transmission of signals through the designed optical communication system. At the receiver end, various performance indicators of the signal, such as Signal-to-Noise Ratio (SNR) and Bit Error Rate (BER), can be evaluated, as well as the impact of FIR filter noise shaping technology on these performance indicators.

Based on the simulation results, it may be necessary to return to MATLAB for parameter adjustments and algorithm optimization, and then use VPI for simulation again to find the best system configuration and signal processing strategies.

By combining the use of VPI and MATLAB in this manner, MATLAB's powerful signal processing capabilities can be utilized to design and optimize the digital part of the communication system, while VPI' s accurate optical models are used to evaluate the performance of the entire system, achieving comprehensive optimization and verification of the optical communication system design.

3.3 Simulation Result

In the simulation, the parameters for DMT and noise shaping are as shown in Figure 6.

```
settings.CarrierCount = 70;          % Number of carriers (in-band frequency sampling points)
settings.CPLength = 32;              % Cyclic prefix length
settings.FFTLength = 224;            % FFT length
settings.InBandSampleCount = 70;     % Number of in-band frequency samples
settings.Order = 7;                  % Filter order
settings.QuantizeBitsCount = 5;      % Number of quantization bits
settings.QuantizeRange = [-1, 1];    % Range for uniform quantization
settings.SymbolCount = 1024;         % Total number of symbols transmitted
settings.TransmitCount = 262144;     % Total number of symbols transmitted
```

Fig. 6. The parameters used in simulation (Photo/Picture credit: Original)

MATLAB Simulation Results is shown in figure 7.

```
>>> main(24,20,'releaseF');
    SNR: 20
    BER: 4.8876e-05
```

```
>>> main(24,20,'releaseT');
    SNR: 20
    BER: 1.7456e-05
```

Fig. 7. MATLAB Simulation Results (Photo/Picture credit: Original)

The MATLAB project was initially subjected to preliminary testing, conducted within an AWGN (Additive White Gaussian Noise) channel. With the weighting coefficient (Ws) set to 24, the Bit Error Rate (BER) without noise shaping was observed at 4.8876e-05. Upon implementing noise shaping, the BER improved to 1.7456e-05, as depicted in Figure 7, indicating a reduction in the error rate.

The MATLAB project was integrated with the VPI project for simulation purposes. Under identical conditions, the weighting coefficient (W_s) was initially set to 1, resulting in Figure 8.

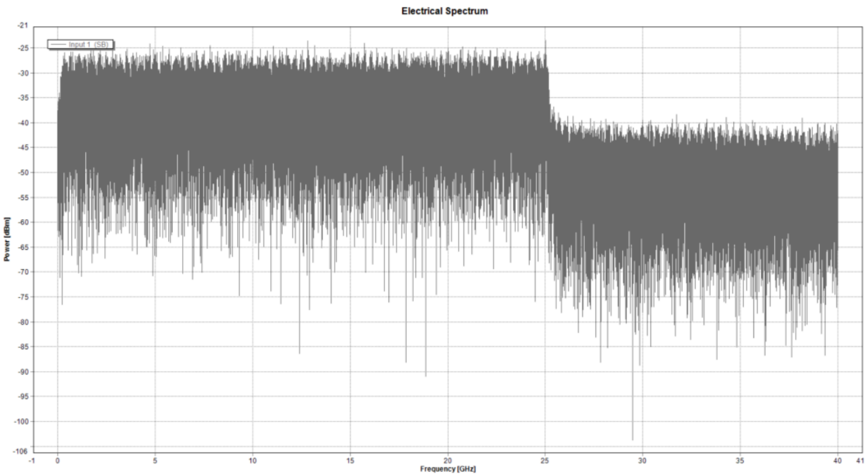

Fig. 8. Ws = 1 (Photo/Picture credit: Original)

Subsequently, setting the weighting coefficient (W_s) to 24 yielded Figure 9.

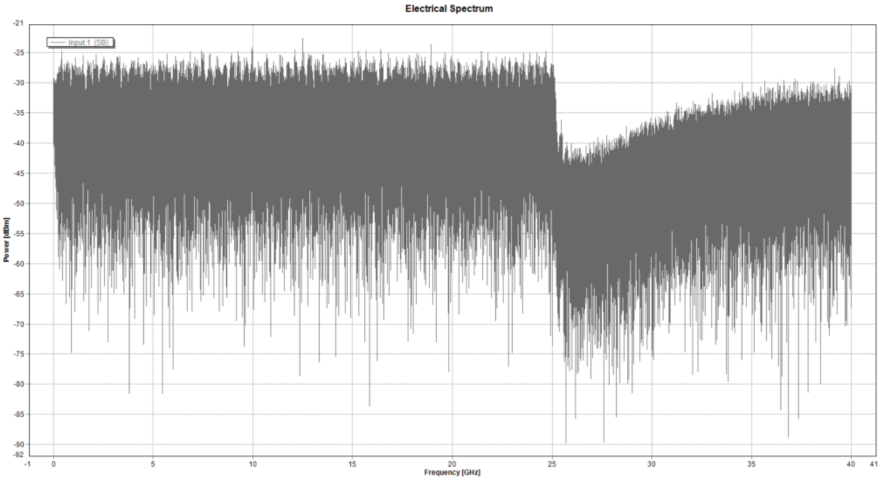

Fig. 9. Ws = 24 (Photo/Picture credit: Original)

Comparing the two images, there is a noticeable lift in the high-frequency section in Figure 9, indicating that noise has been shifted to the high-frequency band, which does not carry information. This achieved noise shaping, with effects consistent with those observed in Figure 4.

Under the condition of ROP = 10mW with (Ws= [12, 24, 36, 48, 60, 72, 84, 96, 108, 120]), the Bit Error Rates are given in table 1. Here, “4bit” denotes a 4 bitDAC with noise shaping, and “4 bit_no_fir” refers to a standard 4 bitDAC.

Table 1. Bit Error Rates

	4 bit	4 bit_no_fir	5 bit	5 bit_no_fir
12	0.064324	0.066405	0.042491	0.045692
24	0.063824	0.067093	0.042190	0.045517
36	0.063322	0.066730	0.042180	0.045685
48	0.064195	0.065815	0.042704	0.045182
60	0.066586	0.066572	0.042620	0.045720
72	0.065333	0.066988	0.042505	0.045486
84	0.065501	0.065783	0.042787	0.045004
96	0.241677	0.066712	0.043171	0.045196
108	0.246254	0.066157	0.042176	0.045416
120	0.064666	0.065850	0.042550	0.045022

To determine the optimal weighting coefficient (Ws), we calculated the Bit Error Rate (BER) under various (Ws) values and different Received Optical Power (ROP) conditions. Figure 10 shows the BER at an ROP of 10mW for (W_s = [12, 24, 36, 48, 60, 72, 84, 96, 108, 120]), where “4bit” represents a 4bitDAC with noise shaping, and “4 bit_no_fir” denotes a standard 4 bitDAC.

The power of a signal characterizes the strength of the received signal. When signals of the same strength are received at the receiver, the Bit Error Rate (BER) with noise shaping is lower, indicating higher performance of the communication system.

Observing table 1, it is found that the optimal (Ws) is 36 for 4-bit quantization, and for 5-bit quantization, the optimal (Ws) is 72, as shown in Figures 10 and 11, which present the corresponding BER-ROP graphs.

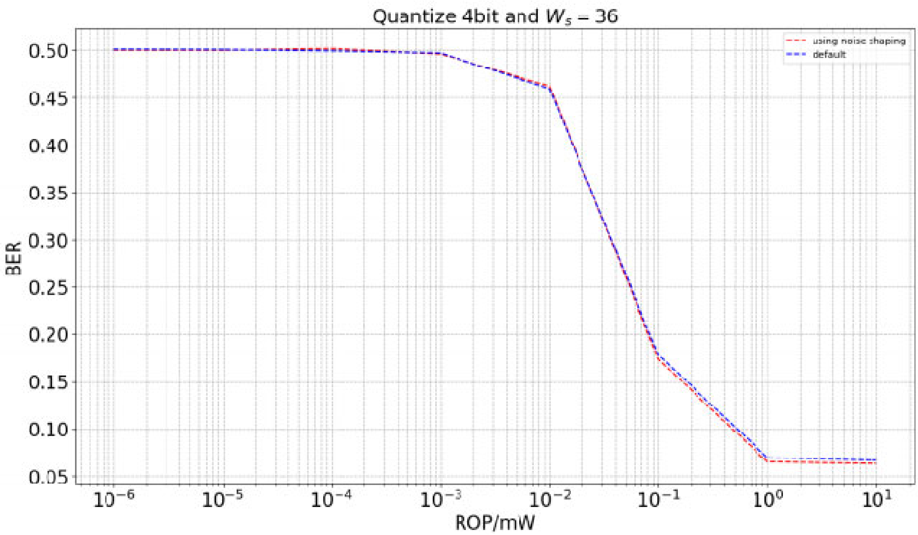

Fig. 10. 4-bit quantization, Ws = 36 (Photo/Picture credit: Original)

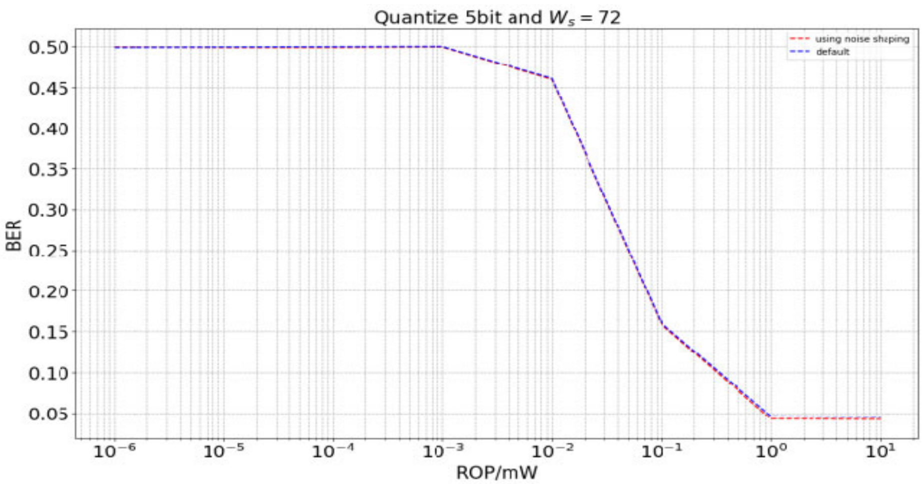

Fig. 11. 5-bit quantization, Ws=72 (Photo/Picture credit: Original)

In Figures 10 and 11, the horizontal axis represents the Received Optical Power (ROP), which is the power of the optical signal received by the receiver. It characterizes the strength of the received signal. When signals of the same strength are received at the receiver, the Bit Error Rate (BER) with noise shaping is lower, indicating a higher performance of the communication system.

4 Conclusion

Integrating MATLAB and VPI projects for simulation, under identical conditions, initially setting the weighting coefficient Ws=1 yields Figure 8, then adjusting the weighting to Ws=24 results in Figure 9. Comparing the two figures, there is an uptick in the high frequency range in Figure 9, indicating that noise has been shifted to the high-frequency band that does not carry information, achieving noise shaping with effects similar to those shown in Figure 4. Observation of Figure 10 reveals that the optimal (Ws) under 4-bit quantization is 36, while under 5-bit quantization, the optimal (Ws) is 72, as depicted in Figures 11 and 12, which are the corresponding BER-ROP (Bit Error Rate - Received Optical Power) graphs. In Figures 10 and 11, the horizontal axis represents the received optical power (ROP), which is the power of the optical signal received by the receiver, indicating the strength of the received signal. When signals of identical strength are received, the use of noise shaping results in a lower bit error rate, indicating higher performance of the communication system.

However, the BER-ROP graphs demonstrate only a marginal enhancement in BER. It is speculated that this outcome arises from the lack of filtering within the reception system. Despite the relocation of noise to the high-frequency band, the absence of filtering at the receiving end continues to exert a substantial influence on performance. The next step involves adding filtering to the simulation program and adjusting to optimize the simulation system.

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