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RESEARCH ARTICLE BIOCHEMISTRY

# Study and Analysis of Baseband Signal Using Eye Diagram

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**ABSTRACT**

This study investigates a two-level baseband transmission system, emphasizing the effects of noise level and transmission rate on signal integrity. The Nyquist criterion for distortionless transmission is validated under varied conditions. An eye diagram is used to visualize the impacts of jitter, signal-to-noise ratio (SNR), and inter-symbol interference (ISI) on data quality. Results show that the eye opening narrows when transmission rates exceed the Nyquist limit, increasing bit error rate (BER). BER is computed using both the Gaussian distribution model and a hardware-based error counter. Findings confirm an exponential rise in BER as input noise increases, with a maximum BER of 0.02328 observed at 0 dB noise level. These results highlight the critical role of noise control and bandwidth constraints in baseband system performance.

# دراسة وتحليل إشارة الحزمة الأساسية باستخدام مخطط العين ومعدل خطأ البت

حنان الغناي محمد أبودربالة [1]

**الكلمات المفتاحية**

معيار نيكويست
التداخل بين الرموز
ثقلق الارسال
مخطط العين
معدل خطأ البت

**الملخص**

تناول هذه الدراسة نظام إرسال أساسي ثنائي المستويات، مع التركيز على تأثير مستوى الضوضاء ومعدل الإرسال على جودة الإشارة. يتم التحقق من معيار نايكويست للإرسال الخالي من التشويه تحت ظروف مختلفة. ويُستخدم مخطط العين لتصوير تأثير التذبذب، ونسبة الإشارة إلى الضوضاء(SNR) ، والتداخل بين الرموز (ISI) على جودة البيانات. تُظهر النتائج أن فتحة العين تضيق عندما تتجاوز معدلات الإرسال حد نايكويست، مما يؤدي إلى زيادة معدل خطأ البت (BER). يتم حساب معدل خطأ البت باستخدام كل من نموذج التوزيع الغاوسي وجهاز عدّ الأخطاء المعتمد على العتاد. تؤكد النتائج حدوث ارتفاع أسي في معدل خطأ البت مع زيادة الضوضاء المدخلة، حيث تم تسجيل أعلى قيمة لمعدل خطأ البت بلغت 0.02328 عند مستوى ضوضاء 0 ديسيبل. وتبرز هذه النتائج الدور الحاسم للتحكم في الضوضاء والقيود المتعلقة بعرض النطاق الترددي في أداء أنظمة الإرسال الأساسي.

## Introduction

Baseband signals, also known as low-pass signals, are those whose spectra range from direct current (DC) up to a limited frequency, often less than 1 MHz. These signals are widely used in digital communication systems for the transmission of binary data, where the analogue input is converted to binary digits through pulse code modulation (PCM). PCM involves three key steps: sampling, quantization, and encoding. Once digitized, these signals are transmitted as pulse-amplitude modulated waveforms via a channel such as coaxial cable or twisted pair wires. A block diagram of a typical baseband transmission system is shown in Fig 1. [1,2].

However, the transmission of baseband signals over practical communication media is susceptible to various sources of distortion. These include quantization noise, sampling jitter, inter-symbol interference (ISI), and channel noise such as thermal or impulse noise. ISI, in particular, becomes pronounced when the channel bandwidth is limited or when the data rate exceeds the Nyquist limit. The Nyquist sampling theorem states that to avoid aliasing and ISI, the sampling frequency must be at least twice the bandwidth of the signal [2].

An important diagnostic tool for evaluating signal integrity in such systems is the eye diagram. It provides a visual representation of how signal degradation—due to noise, jitter, and ISI—affects data transmission. By observing the “eye opening,” one can estimate the system’s margin for noise immunity and timing accuracy. Additionally, the bit error rate (BER) is used as a quantitative measure of transmission quality. BER can be calculated using statistical models, such as the Gaussian error function, or measured directly using error counters in a hardware setup [2,3].

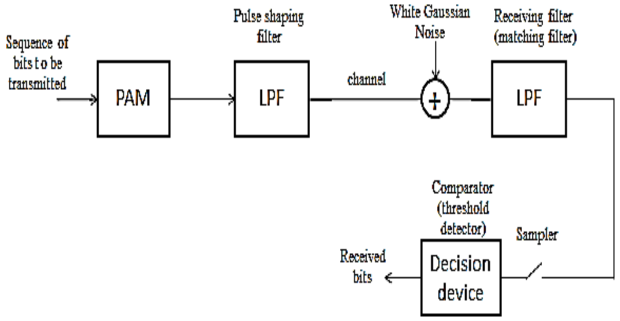


**Fig. 1**: Block diagram of baseband transmission

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Several studies have employed eye diagrams and BER analysis to characterize digital transmission systems, especially in high-speed and bandwidth-limited environments [3-5]. Despite their utility, there is a lack of experimental studies that combine both eye diagram and BER analysis in real baseband hardware implementations under varying noise and rate conditions. The objective of this study is to experimentally evaluate a two-level baseband transmission system under varying noise levels and data rates using eye diagram visualization and BER computation. The study aims to validate the Nyquist criterion, observe ISI and jitter effects, and compare BER results obtained from two different methods. These findings give an understanding of performance limitations in baseband communication systems.

## Methodology

The experiments were conducted at the University of Essex laboratory. The experimental setup for evaluating baseband signal performance is designed to simulate real-world transmission over a noisy channel.

### Experimental setup

The block diagram in Fig. 2 illustrates the full system, consisting of a binary data generator, a length of 75-Ω coaxial cable channel, a noise source, and a BER measurement unit. A data generator produces a sequence of binary bits at a variable clock rate. These bits are transmitted through a 75-ohm coaxial cable to emulate a real transmission line. An external white Gaussian noise source is introduced at the channel input to replicate interference. The receiver section includes a comparator, D-type flip-flop, and an error counter to detect bit mismatches and compute BER. Timing information is extracted from the received signal using the flip-flop circuit [6].

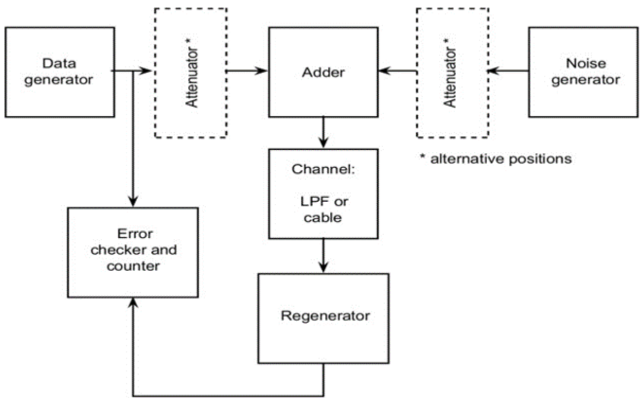


**Fig. 2**: Block diagram of the experimental system [6]

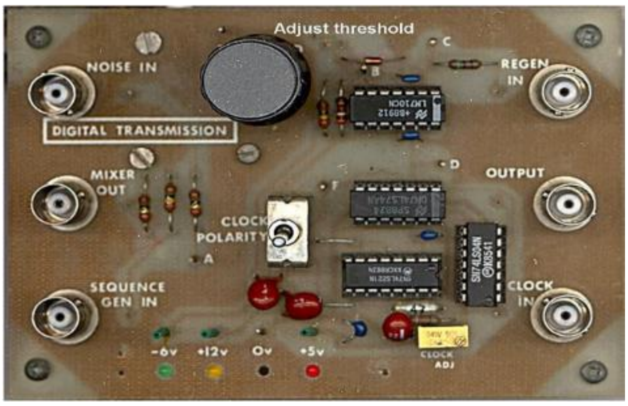


**Fig. 3:** The experimental board [6]

As indicated in Fig 4, the experimental board, clock, coaxial cable, and sequence generator are connected. To ensure impedance matching and avoid signal reflection, all devices operate at 75-ohm impedance, and the cable is terminated with a dummy load of equal resistance. The comparator threshold voltage is manually set at 50% of the peak input signal using an oscilloscope, ensuring symmetrical detection for high and low logic levels. The comparator's non-inverting input is linked to the channel's output and the comparator output is fed to the D-type flip flop clock so phase and polarity adjustments are possible. [6]

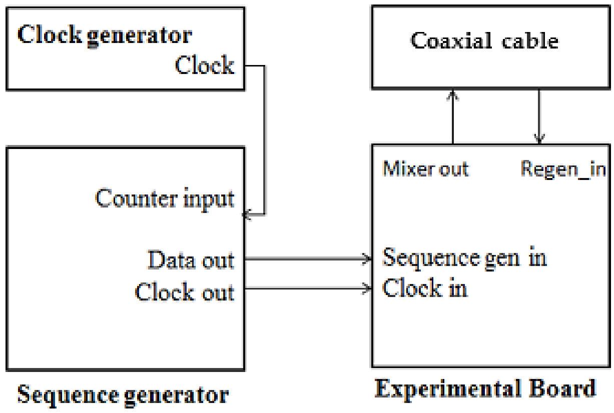


**Fig. 4**: Experimental setup

### BER computation

The BER is calculated using two different methods:

**Hardware-based error counting:**

Every time an error is generated, the error counter is internally configured to generate three pulses. For the specified SNR, the number of errors is counted over a ten-second interval at a transmission rate of 1 MHz. The BER is then computed using the formula The transmission rate is 1MHz [6]:

$$\mathrm{BER} = \frac{\text{Error Count}}{3 \times 10 \times 10^6} \tag{1}$$

**Theoretical Gaussian error probability:**

For this approach, the BER is estimated based on the standard Gaussian tail function. In Table 2, the BER calculations are presented using error probability. The error probability represents the likelihood that the noise will be of a sufficient amplitude and polarity to cancel the low level of the signal in the presence of RMS noise, an error happens when the noise peak exceeds half peak-peak signal amplitude (A/2) (the comparator threshold). The BER was determined from tail function curve, and given by eq. (2) [6]:

$$\mathrm{BER} = \mathrm{T}\left[\frac{\mathrm{A}}{2 \times \mathrm{n}}\right] \tag{2}$$

Where,

A: the voltage difference between at the maximum eye opening (1.5V),

(n): RMS value of noise measured from the voltammeter.

(T): standard Gaussian tail function

## Results and Discussions

The performance of the 2-level baseband transmission system was assessed using eye diagrams and BER calculations under different noise levels and data rates. The visual and numerical outcomes are presented and discussed in this section.

### The Eye diagram analysis

The eye diagram, shown in Fig 5, was captured by triggering the oscilloscope using the transmitted data clock.. The "curved" portions of the eye pattern are caused by signal transitions between high and low logic levels, which happen in a finite amount of time due to the channel's limited bandwidth (500 kHz).

The straight lines at the top and bottom of the eye are shaped when the logical levels do not change between clock intervals. The vertical opening represents the SNR during sampling. It shows the noise-induced bit error margin, meaning errors happen when the noise peak is greater than half of the eye-opening. Conversely, the horizontal opening shows the timing inaccuracy margin that can arise from an imperfectly recovered clock. The jitter error has more effect at higher rates and it is indicated by the misalignment of rise and fall times that causes a kind of "grid", or spreading, and appears clearly towards the end of the bit intervals. [7] The maximum eye opening was measured to be 1.50V.

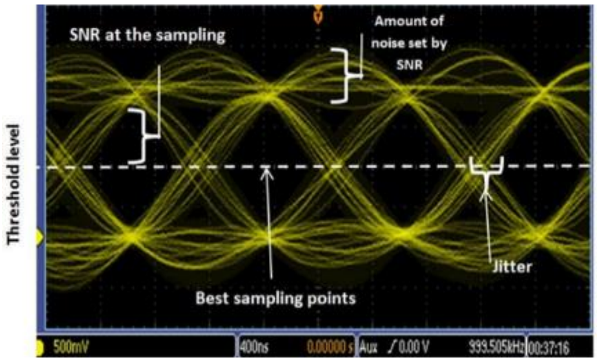


**Fig. 5**: System eye diagram

Fig 6 illustrates how varying the clock rate affects the eye pattern: At rates below 1 MHz, a clear and wide eye opening is observed (Fig 6a), consistent with Nyquist's criterion. However when exceeding Nyquist limit, at rates above 1 MHz, the eye narrows significantly (Fig 6b), indicating the onset of inter-symbol interference (ISI) and timing jitter, which degrade signal integrity. Also, as data rates increase, jitter effects become more pronounced, resulting in waveform "spreading" and timing misalignment, particularly near the transitions.

**BER Measurements**

Two methods were used to compute BER: hardware error counting and theoretical Gaussian probability. Table 1 presents BER values calculated by counting errors over 10 seconds and using Equation (1). The BER increases exponentially as the input noise level rises. For instance, at –10 dB input noise, no errors were detected, whereas at 0 dB, the BER reached 0.02328.

Table 2 summarizes the BER calculated using the Gaussian tail function, based on noise RMS voltage.

The BER results are displayed in Fig 7 (a) and (b) using error count and error probability calculations respectively. Similar behavior of growing number of errors as SNR decreases (input noise increases) is shown in both figures. Although both methods show similar trends—increasing BER with higher noise—the absolute values differ due to assumptions in signal levels and measurement methods.

Fig 8 and 9 demonstrate how increasing noise narrows the eye diagram. For example: At –18 dB, the eye opening is wide and symmetric. At 0 dB, the eye almost closes, indicating a high likelihood of bit errors due to reduced margin for timing and voltage thresholds.

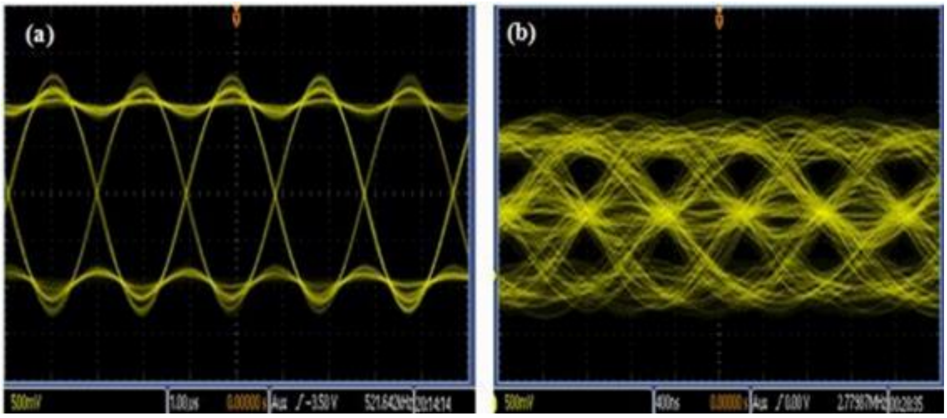


**Fig. 6:** Eye diagram at different clock rates (a) below 1MHz, (b) above 1MHz

**Table 1**: The BER calculation using the error count

| $N_{in}(dB)$ | S+N (RMS-V) | N (RMS-V) | S=(S+N)-(N) | SNR(S/N) | Error count | BER |
|---|---|---|---|---|---|---|
| **-10** | 0.56 | 0.1 | 0.46 | 4.6 | 0 | 0 |
| **-9** | 0.58 | 0.115 | 0.465 | 4.043478 | 43 | 1.43E-06 |
| **-8** | 0.59 | 0.125 | 0.465 | 3.72 | 332 | 1.11E-05 |
| **-7** | 0.595 | 0.14 | 0.455 | 3.25 | 1789 | 5.96E-05 |
| **-6** | 0.595 | 0.16 | 0.435 | 2.71875 | 6589 | 0.00022 |
| **-5** | 0.6 | 0.185 | 0.415 | 2.243243 | 20852 | 0.000695 |
| **-4** | 0.61 | 0.215 | 0.395 | 1.837209 | 50650 | 0.001688 |
| **-3** | 0.615 | 0.235 | 0.38 | 1.617021 | 112502 | 0.00375 |
| **-2** | 0.64 | 0.265 | 0.375 | 1.415094 | 227356 | 0.007579 |
| **-1** | 0.65 | 0.3 | 0.35 | 1.166667 | 412741 | 0.013758 |
| **0** | **0.68** | **0.31** | **0.37** | **1.193548** | **698398** | **0.02328** |

Where; $Nin$: noise input from the Gaussian noise source S+N: signal plus noise measured from; RMS voltammeter N: RMS noise measured from the RMS voltammeter; S: signal level which is calculated by subtracting (S+N)-(N); SNR: signal to noise ratio which calculated by dividing signal level (S) by noise level (N).

**Table 2**: The BER calculation using the error probability

| $N_{in}(dB)$ | Noise (RMS-V) | A/2n | BER |
|---|---|---|---|
| **-10** | 0.1 | 7.5 | 3.191E-14 |
| **-9** | 0.115 | 6.521739 | 4.016E-11 |
| **-8** | 0.125 | 6 | 9.866E-10 |
| **-7** | 0.14 | 5.357143 | 2.867E-07 |
| **-6** | 0.16 | 4.6875 | 0.0000013 |
| **-5** | 0.185 | 4.054054 | 3.167E-05 |
| **-4** | 0.215 | 3.488372 | 0.0003369 |
| **-3** | 0.235 | 3.191489 | 0.0006871 |
| **-2** | 0.265 | 2.830189 | 0.002555 |
| **-1** | 0.3 | 2.5 | 0.00621 |
| **0** | **0.31** | **2.419355** | **0.0082** |

These visual indicators align with the numerical BER results and highlight the combined effects of noise, ISI, and jitter on transmission performance.

## Conclusion

This study examined the performance of a two-level baseband digital transmission system by analyzing eye diagrams and bit error rates (BER) under varying noise conditions and transmission rates. The results demonstrated a clear relationship between increased input noise and degradation in signal quality.

The maximum eye opening observed was 1.50 V, which decreased with higher transmission rates or noise levels. BER increased exponentially with noise input. At 0 dB noise, BER peaked at 0.02328 (hardware-based), while Gaussian-based estimates showed similar trends with slight numerical differences. At transmission rates exceeding 1 MHz, both inter-symbol interference (ISI) and jitter became pronounced, causing the eye diagram to close and increasing error

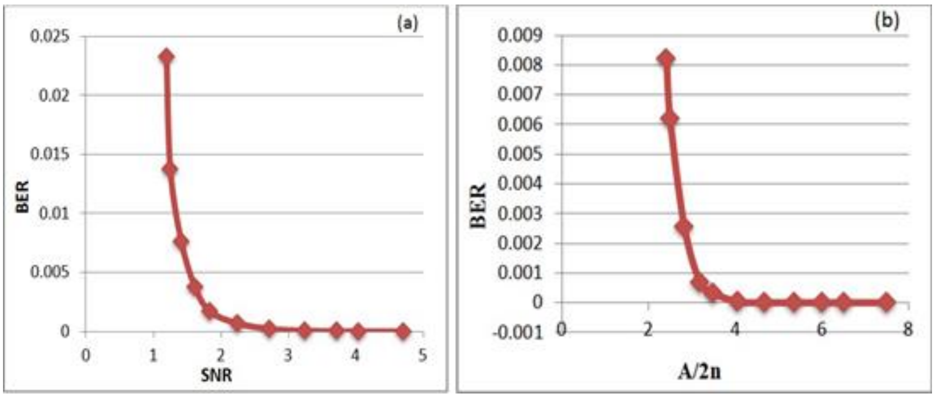


**Fig. 7**: BER measurement using (a) error count (b) error probability.

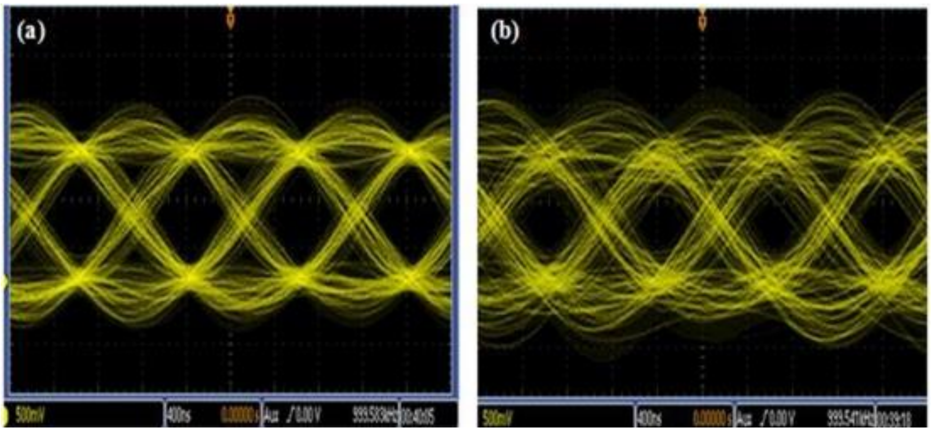


**Fig. 8**: The eye diagram at different noise input (a) noise level of -18dB (b) noise level of -8 dB

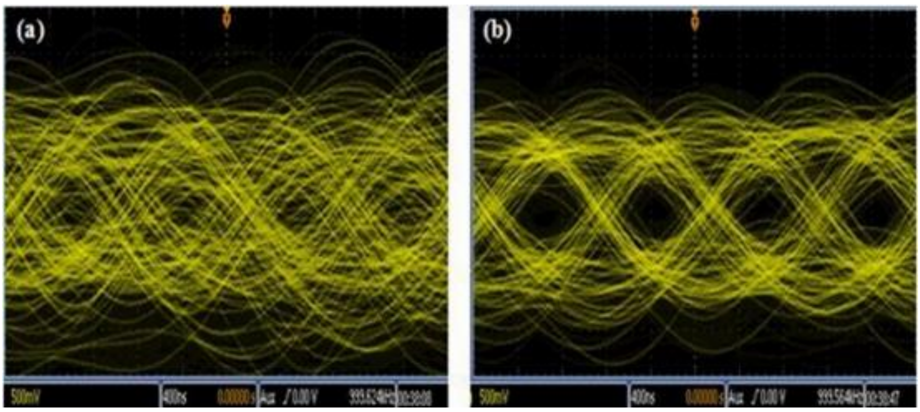


**Fig. 9:** The eye diagram at different noise input (a) noise level of 0dB (b) noise level of -5 dB

likelihood. The experiment confirmed the practical implications of Nyquist's criterion, showing that exceeding the ideal data rate leads to severe performance degradation. Overall, both visual (eye diagram) and analytical (BER) methods proved effective in diagnosing transmission quality and identifying the causes of signal distortion in baseband systems.

## Recommendations

Based on the results and limitations of this study, the following recommendations are proposed:

- Enhanced Filtering: Implementing advanced filtering at the receiver can reduce ISI effects, especially at higher transmission rates.
- Jitter Compensation Techniques: Employing clock recovery and synchronization mechanisms can minimize timing jitter impacts.
- Future Work: Further studies should explore multilevel baseband systems, wider bandwidth channels, and the use of error-correcting codes to improve performance under noisy conditions.
- Future evaluations could include statistical regression or confidence intervals for BER estimates to provide more robust assessments.

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