1.5. Analog and Digital Signals

**Analog** – signal varies continuously with time, needs high signal-to-noise ratio

**Digital** – discrete values, binary

- $T_B$ – bit period or time
- $B$ – bit rate = $1/T_B \propto$ bandwidth
- Example:
  - ASCII code - 7 bit (0-127)
  - a-z (65-90)
  - A-Z (97-122)

Digital modulation requires higher bandwidth than analog. A digital “bit” of width $T$, where $T < T_B$, has a Fourier transform

$$\text{rect}(t/T) \leftrightarrow \text{sinc}(fT).$$

The first zero of the sinc() function occurs when $f = 1/T > B$. Therefore, the bandwidth required of the transmission channel is greater than the actual bit-rate. However, digital modulation results in better noise performance as nonlinearities in the channel do not degrade the signal as much. For example, laser diode modulation could produce harmonic distortion in an analog signal if the diode is not properly biased, as shown in the figure. For a nonlinear transfer function, a square wave still maps to a square wave.
1.5.1. Analog to Digital Conversion

Many signals originate in analog format (such as voice and video) and can be converted to digital. This conversion consists of three steps:

1. Sample analog signal at discrete time intervals $1/f_s$, with sampling frequency $f_s$
2. Quantize sampled value into discrete set of $M$ values
3. Digitize into binary representation of $\log_2 M$ bits

Quantization noise is minimized by a number of discrete levels $M$ that satisfies $M = A_{\text{max}}/A_N$, where

- $A_{\text{max}} = \text{maximum signal amplitude}$
- $A_N = \text{RMS noise amplitude of analog signal}$
This means each quantization interval $\Delta A = A_N$. There is no sense in having $\Delta A < A_N$, as it provides no additional information.

$$\frac{A_{\text{max}}}{A_N} = \text{amplitude dynamic range}$$

The signal-to-noise ratio is defined

$$\text{SNR} = 10 \log \left( \frac{P_{\text{max}}}{P_{\text{noise}}} \right) = 10 \log \left( \frac{A_{\text{max}}^2/R}{A_n^2/R} \right) = 20 \log \left( \frac{A_{\text{max}}}{A_N} \right) = 20 \log M$$

SNR will ultimately determine the bit-error-rate (BER).

For binary modulation, the number of binary digits, or bits, needed is $m = \log_2 M$.

<table>
<thead>
<tr>
<th>Binary representation</th>
<th>Quantized value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0 0</td>
<td>0</td>
</tr>
<tr>
<td>0 0 1</td>
<td>1</td>
</tr>
<tr>
<td>0 1 0</td>
<td>2</td>
</tr>
<tr>
<td>0 1 1</td>
<td>3</td>
</tr>
<tr>
<td>1 0 0</td>
<td>4</td>
</tr>
<tr>
<td>1 0 1</td>
<td>5</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

1.5.2. Digital formats

The physical digital formats used with optical pulses are pulse-position modulation, pulse duration modulation, and pulse code modulation.

In **PCM (pulse code modulation)**, the pulse is either present (1) or not (0). PCM is also known as on-off keyed (OOK), which is the most common modulation format in optical systems.
1.5.3. Bandwidth requirements of digital PCM (OOK)

The total bit rate of digital PCM is \( B = mf_s \geq 2\Delta f \log_2 M \), which can be written in terms of the SNR as \( B = (\Delta f/3)\text{SNR} \). As an example, for \( \text{SNR} = 30 \text{ dB} \), \( B \sim 10 \Delta f \), which requires at least a factor of 10 greater bandwidth than analog, where \( \Delta f \) is the original analog bandwidth.

For a typical audio signal (i.e. telephone), \( \Delta f \sim 4 \text{ kHz} \). In order to obtain 30 dB SNR, the digital bit-rate must be greater than 40 kb/sec, and is usually 64 kb/sec. In this case, the sampling frequency \( f_s = 8 \text{ kHz} \), and each sample consists of \( m = 8 \) bits (i.e. \( M = 256 \) quantized levels).

For reference, AM radio has a bandwidth of 10 kHz, and FM radio 200 kHz. TV stations transmit with about 6 MHz of bandwidth. For real-time, uncompressed video, \( B \sim 81 \text{ Mb/sec} \) using 9-bit sampling at 9 MHz. The audio track is sampled at 30 kHz with 8-bit quantization, for a total of 240 kb/s. Note that a T1 line = 1.544 Mb/sec, so digital video requires at least a T3C line 91.053 Mb/s. Compressed video can be transmitted at 5 Mb/s, while compressed HD requires 20 Mb/s.

1.6. Modulation formats

The optical carrier can be represented by

\[
E(t) = \frac{1}{2} A e^{i(\omega_ot + \phi)} + cc
\]

Any of the three major properties of the carrier can be modulated to represent data - amplitude, phase, and frequency.

Analog modulation

1. amplitude (AM, change A)
2. frequency (FM, change \( \omega = d\phi/dt \))
3. phase (PM, change \( \phi \))

Digital modulation

1. ASK (amplitude shift keyed)
2. FSK
3. PSK

For two levels, ASK is the most common, using \( A = 0 \) and \( A = A_o \). This is also called OOK, or on-off keyed. There are two binary OOK representations in use today in optical communications systems - return to zero (RZ), and non-return to zero (NRZ). NRZ is the current standard, but RZ will most likely dominate in future systems.
### 1.6.1. Detection schemes

1. Coherent

2. IM/DD intensity modulation/direct detection. Electronics determine if bit is 0 or 1. SNR determines accuracy of decision.