A line code is an assignment of a symbol or pulse to each zero or one to be transmitted. Digital data is represented by baseband data formats known as line codes.

In other words, what shape will the waveform take?
Preliminary: Bit Rate vs. Symbol Rate (or Baud Rate)

The speed of data is commonly expressed in bits/second or bytes/second. The **data rate** $R_b$ is related to the **bit period** $T_b$ (duration of a bit).

$$R_b = \frac{1}{T_b}$$

The bit rate is commonly referred to as the **channel capacity**.

Communication systems use **symbols** to convey information. A symbol may be one bit per symbol (called **binary**), or a group of bits, or a collection of defined voltage levels (multiple level symbols), etc.

The **symbol rate** $R_{sybl}$ is related to the symbol’s period (or duration) $T_s$ by

$$R_{sybl} = \frac{1}{T_s}$$

The symbol rate is also called **Baud rate**. Bit rate $R_b$ can be written as

$$R_b = R_{sybl} \times \log_2(\eta) = R_{sybl} \times n$$

where $\eta = 2^n = \text{number of levels (for } n \text{ bits per symbol)}$. 
**Signal-to-Noise Ratio vs. Energy/Bit-to-Noise Ratio**

In analog and digital communications, **signal-to-noise ratio**, usually written \( S/N \) or **SNR**, is a measure of **signal** strength relative to background **noise** strength. The **ratio** is usually expressed in decibels (dB) and equals \( 10 \cdot \log_{10}[S/N] \).

Another metric that is often more useful in digital systems is the **energy per bit-to-noise power ratio**, denoted by \( E_b/N_0 \).

Define: \( R_b = \) bit rate (in bits per second)  
\( S = \) total signal power (watts)  
\( E_b = \) energy per bit (in joules/bit)  
\( N = \) total noise power (over entire bandwidth \( B \) in Hz)  
\( N_0 = \) noise spectral density \((N = N_0 \cdot B \text{ where } B = \text{bandwidth})\)

Then,

\[
\frac{S}{R_b} = E_b \quad \text{and} \quad \frac{E_b}{N} = \frac{S}{R_b \cdot N} \quad \text{and} \quad \text{SNR} = \frac{R_b E_b}{N_0 B}
\]

Increasing the data rate \( R_b \) increases the **SNR**. However, in general it also increases the noise in the denominator, which lowers the **SNR**.
Signal-to-Noise Ratio vs. Energy/Bit-to-Noise Ratio (continued)

In digital communications systems the $E_b/N_0$ ratio can be thought of as a “normalized signal-to-noise ratio.”

We can roughly equate signal power to energy per bit by

$$E_b = P_{\text{signal}} \cdot T_S,$$

where $T_S$ is the symbol period,

and the noise power per hertz, denoted by $N_0$, is the total noise power $N$ divided by bandwidth $B$.

$E_b/N_0$ is commonly used to as the primary variable in establishing the bit error rate for all modulation schemes.
A line code is a specific code (with precisely defined parameters) used for transmitting a digital signal over a channel. Line coding is used in digital data transport – the pattern of voltage, current or photons used to represent digital data on a transmission link is called line encoding.
**Unipolar – RZ and NRZ** (aka “On-Off Keying”)

Unipolar RZ and NRZ both have a DC component.

- **State “1”** ⇒ Pulse of amplitude +A
- **State “0”** ⇒ No pulse

---

### ADVANTAGES

1. Simplicity
2. Doesn’t require a lot of bandwidth

### DISADVANTAGES

1. Presence of DC level
2. Contains low-frequency components (leads to drooping)
3. No clocking component to synchronize to at receiver
4. Long string of zeros causes loss of synchronization
Signal droop distortion is due to AC coupling.
Polar – RZ and NRZ

Polar RZ takes twice as much bandwidth as polar NRZ.

**ADVANTAGES**
1. Simplicity
2. No DC component

**DISADVANTAGES**
1. Can contain low-frequency components (leads to signal drooping)
2. No clocking component to synchronize to at receiver
3. No error correction capability

State “1” ⇒ Pulse of amplitude +A
State “0” ⇒ Pulse of amplitude -A

Adjacency table:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_b = T_s/2$</td>
</tr>
</tbody>
</table>

Diagram showing RZ and NRZ waveforms.
Power Spectral Density Example: Polar NRZ Signal

There is no DC component.

\[ R_b = \frac{1}{T_b} \]

Sinc squared function

**Bipolar NRZ**

Uses three levels of signal level (+A, 0, -A) and has “**Alternate Mark Inversion**” (AMI)

<table>
<thead>
<tr>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. No DC component</td>
<td>1. No clocking component to synchronize to at receiver</td>
</tr>
<tr>
<td>2. Less bandwidth than for unipolar &amp; polar NRZ</td>
<td>2. Limited error correction capability</td>
</tr>
<tr>
<td>3. No signal droop problem</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-A</td>
<td>1</td>
</tr>
</tbody>
</table>

State “1” ⇒ Alternating levels of +A and -A
State “0” ⇒ No pulse
Bipolar RZ

Uses three levels of signal level (+A, 0, -A)
Has “Alternate Mark Inversion” – AMI

State “1” ⇒ Alternating levels of +A and -A
State “0” ⇒ No pulse

<table>
<thead>
<tr>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. No DC component</td>
<td>1. No clocking component to synchronize to at receiver</td>
</tr>
<tr>
<td>2. No signal droop problem</td>
<td>2. Limited error correction capability</td>
</tr>
</tbody>
</table>
Manchester (Bi-Phase or Split-Phase) Encoding

The duration of a symbol is divided into two halves.

There is a transition at the center of every symbol period.

State “1” \(\Rightarrow\) +A in 1\(^{st}\) half of \(T_s\) and –A in 2\(^{nd}\) half

State “0” \(\Rightarrow\) -A in 1\(^{st}\) half of \(T_s\) and +A in 2\(^{nd}\) half

<table>
<thead>
<tr>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. No DC component</td>
<td>1. Greater bandwidth required for this waveform</td>
</tr>
<tr>
<td>2. No signal droop problem</td>
<td>2. No error correction capability</td>
</tr>
<tr>
<td>3. Easy to synchronize to the waveform</td>
<td></td>
</tr>
</tbody>
</table>
Manchester (Bi-Phase or Split-Phase) Encoding

- Manchester encoding is a form of binary phase-shift keying (BPSK).
- It is designed to encode both the clock and the data in a bit stream.
- This is also referred to “self-synchronizing data steam.”
- Manchester encoding has the disadvantage of requiring higher frequencies.
- It is used in Ethernet (IEEE 802.3 standard) with lower data rates.
- Also used for consumer IR protocols and in some RFID systems.
Differential Manchester (Bi-Phase) Encoding

Manchester (or Bi-Phase)

0 → 1 
1 → 0

Transition always is in middle of period of symbol period
1 → Forces transition at beginning
0 → Do nothing

Differential Manchester
Polar Quaternary NRZ (2B1Q)

State “00” \( \Rightarrow \) Voltage level at \(-3A/2\)
State “01” \( \Rightarrow \) Voltage level at \(-A/2\)
State “10” \( \Rightarrow \) Voltage level at \(+A/2\)
State “11” \( \Rightarrow \) Voltage level at \(+3A/2\)

Also referred to as \( \text{mBnL} \) coding, where \( m \) is the length of the binary pattern, and \( n \) is the number of levels \( (L = B \text{ for binary } (n = 2), L = T \text{ for ternary } (n = 3) \) and \( L = Q \text{ for quaternary } (n = 4) \). Hence, polar quaternary would be \( 2B1Q \).

Used in ISDN networks and in HDSL digital subscriber lines.

Integrated Services Digital Network (ISDN) is a set of communication standards for simultaneous digital transmission of voice, video, data, and other network services over the traditional circuits of the public switched telephone network.
### Bandwidth Efficiency

<table>
<thead>
<tr>
<th>Modulation format</th>
<th>Theoretical bandwidth efficiency limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSK</td>
<td>1 bit/second/Hz</td>
</tr>
<tr>
<td>BPSK</td>
<td>1 bit/second/Hz</td>
</tr>
<tr>
<td>QPSK</td>
<td>2 bit/second/Hz</td>
</tr>
<tr>
<td>8PSK</td>
<td>3 bit/second/Hz</td>
</tr>
<tr>
<td>16 QAM</td>
<td>4 bit/second/Hz</td>
</tr>
<tr>
<td>32 QAM</td>
<td>5 bit/second/Hz</td>
</tr>
<tr>
<td>64 QAM</td>
<td>6 bit/second/Hz</td>
</tr>
<tr>
<td>128 QAM</td>
<td>7 bit/second/Hz</td>
</tr>
<tr>
<td>256 QAM</td>
<td>8 bit/second/Hz</td>
</tr>
</tbody>
</table>
What Are the Primary Considerations When Comparing Line Codes?

1. We want the transmission bandwidths to be as small as possible.

1. Power efficiency – Keep power as low as possible.

2. Error detection and correction capability – error correcting codes are a special topic

4. Favorable Power Spectral Density – We want zero power at DC \( f = 0 \) to avoid baseline drift.

5. Adequate timing content – Often we must extract the timing or clock information from the signal.

6. Transparency – This means for every possible sequence of data the coded signal is received faithfully.

7. Signal is easily regenerated by repeaters.
Review: Signal Energy and Power

Review: The energy and power associated with signal $g(t)$ are defined:

For a real signal $g(t)$ the signal energy $E_g$ is defined to be

$$E_g = \int_{-\infty}^{\infty} g^2(t) dt$$

For a complex signal $g(t)$ the signal energy $E_g$ is defined to be

$$E_g = \int_{-\infty}^{\infty} |g(t)|^2 dt$$

The signal power is more useful. For a real or complex signal $g(t)$ the signal power $P_g$ is defined to be

$$P_g = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} |g(t)|^2 dt$$

The signal power $P_g$ is the time average (mean) of the signal amplitude squared (sometimes called the “mean-square” value of $g(t)$).
Concept of Power Spectral Density

Suppose we have signal $g_T(t)$ with Fourier transform $G_T(f)$. The subscript $T$ indicates a signal of finite duration.

$$\text{Power of } g(t) = P_g = \lim_{T \to \infty} \frac{1}{T} \left[ \int_{-\infty}^{\infty} |G_T(f)|^2 \, df \right]$$

Then the **power spectral density** (PSD) is defined as

$$S_g(f) = \lim_{T \to \infty} \frac{|G_T(f)|^2}{T}$$

The power is the area under a PSD. PSD is a positive, real and even function of frequency $f$. Example: If $g(t)$ is a voltage signal, then the units of the PSD are volts-squared per hertz ($V^2/\text{Hz}$).

The power spectral density function (PSD) gives the strength of the variations (energy) of $g_T(t)$ as a function of frequency $f$. 

---

The power spectral density function (PSD) gives the strength of the variations (energy) of $g_T(t)$ as a function of frequency $f$. 

Example: Power Spectral Density of Human Speech

Spectrum of a voice signal over a 15 second duration:

Time Domain

Frequency Domain

Voltage: waveform of speech

PSD

Frequency from 0 Hz to 4,000 Hz
Power Spectral Density of NRZ and Polar NRZ Waveforms

Power Spectral Density of Unipolar RZ, Bipolar RZ & Manchester Waveforms

Comparing Power Spectral Densities for Polar, Bipolar and Manchester

\[ R_b = \frac{1}{T_b} \]

(also known as Manchester)
# Qualitative Comparison of Line Coding Schemes

<table>
<thead>
<tr>
<th>Line Code</th>
<th>Simple</th>
<th>BW</th>
<th>DC component</th>
<th>Error Correct ?</th>
<th>Clock Sync</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unipolar NRZ</td>
<td>Yes</td>
<td>Low</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Unipolar RZ</td>
<td>Yes</td>
<td>$2 \times$ BW</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Polar NRZ</td>
<td>Yes</td>
<td>Moderate</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Polar RZ</td>
<td>Yes</td>
<td>$2 \times$ BW</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Bipolar NRZ (AMI)</td>
<td>Moderate</td>
<td>Smaller BW</td>
<td>No</td>
<td>Single error capability</td>
<td>No</td>
</tr>
<tr>
<td>Bipolar RZ</td>
<td>Moderate</td>
<td>Smaller BW</td>
<td>No</td>
<td>Single error capability</td>
<td>No</td>
</tr>
<tr>
<td>Manchester</td>
<td>No</td>
<td>Greater BW</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Comparing Line Coding Schemes

1. Unipolar NRZ and unipolar RZ are unipolar only need a single-sided power supply to implement them. But polar NRZ, polar RZ, AMI and Manchester require dual power supplies.

2. AMI receivers must detect three levels. All others need only detect two levels.

3. Polar NRZ, polar RZ and Manchester delivers a pulse in every symbol period. This is not true of unipolar NRZ, unipolar RZ, and AMI. A long sequence of 0s can be mistaken as a transmission failure.

4. AMI has a built-in error detecting capability because any 0 is interpreted as a 1, or a 1 is interpreted as a 0; it violates the rules for AMI coding scheme.
Interpreting Eye Diagrams

86100D Infinium DCA-X Wide-Bandwidth Oscilloscope Mainframe
Oscilloscope with Memory for Displaying Multiple Traces

Display window of oscilloscope – trigger sets the beginning of each trace or window

Data stream of pulses

PRBS (pseudo-random bit stream) is generated For testing BER.

Project all frames onto display

(a)
Bit Error Rate (BER) Measurement

\[ BER = \frac{\text{Number of bit errors}}{\text{Total number of bits transmitted}} \]

How many bits in the PRBS bit pattern stream?
The lowest \( \text{BER}_{\text{min}} \) to be measured should have a PRBS length equals \( 3 \times (1/\text{BER}_{\text{min}}) \). Example: For \( \text{BER}_{\text{min}} = 10^{-9} \), then length > \( 3 \times 10^9 \) bits.
Eye Diagrams for Digital Signals

In telecommunication, an **eye pattern**, also known as an **eye diagram**, is an oscilloscope display in which a digital signal from a receiver is repetitively sampled and applied to the vertical input, while the data rate is used to trigger the horizontal sweep.

![Eye Diagrams](image-url)
Example Eye Diagram
What is this Eye Diagram telling us?

Waveform 2
Bit Error Rates and Bit Error Ratios

In digital transmission, the number of bit errors is the number of received bits of a data stream over a communication channel that have been altered due to noise, interference, distortion or bit synchronization errors.

The bit error rate (BER) is the number of bit errors per unit time. The bit error ratio (also BER) is the number of bit errors divided by the total number of transferred bits during a studied time interval.
**Intersymbol Interference (ISI)**

ISI is unwanted interference from adjacent (usually previous) symbols

ISI is caused by dispersion and other non-ideal transmission in channels.
Quadrature Amplitude Modulation

BPSK

QPSK

16-QAM
Example: Bit Error Rates For M-ary Coding
Examples: Bit Error Rates in a Communication System

Probability of bit error rate $\log(P_b)$ vs. $E_b/N_0$
Advantages of Digital Over Analog For Communications

1. Digital is more robust than analog to noise and interference†
2. Digital is more viable to using regenerative repeaters
3. Digital hardware more flexible by using microprocessors and VLSI
4. Can be coded to yield extremely low error rates with error correction
5. Easier to multiplex several digital signals than analog signals
6. Digital is more efficient in trading off SNR for bandwidth
7. Digital signals are easily encrypted for security purposes
8. Digital signal storage is easier, cheaper and more efficient
9. Reproduction of digital data is more reliable without deterioration
10. Cost is coming down in digital systems faster than in analog systems and DSP algorithms are growing in power and flexibility

† Analog signals vary continuously and their value is affected by all levels of noise.