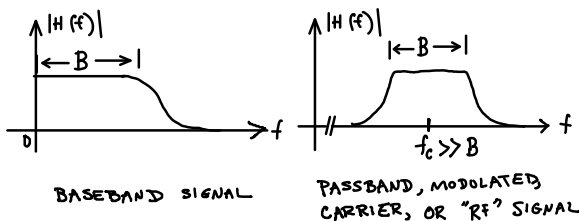


## Line Codes

### Baseband vs Modulated Signals

The frequency response of some channels, typically those using wired channels, extends from zero (DC) up to some maximum frequency. These are called baseband channels. Examples of baseband channels include twisted pair and co-ax.

Other communication systems, typically those using wireless channels or radio frequencies (RF), typically use a frequency range that is a small fraction of the center frequency. These systems use a process called modulation to shift a baseband signal up to the channel frequency. An example is a radio channel.

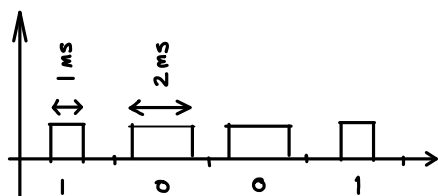


**Exercise 1:** Approximately what frequencies are used by each of the following: Telephones? AM broadcasting? Ethernet LAN? Cable TV? Which are baseband channels?

### Lines Codes

Line codes are the voltage or current waveforms used to represent data when it is transmitted over a baseband channel.

For example, a data value of 0 could be represented by a 1ms pulse and a data value 1 could be represented by a 2ms pulse.



There are dozens of different line codes in use. They have been developed to meet different types of

channels, different data rates, different implementation technologies and different cost/performance requirements. We will study the characteristics of line codes and look at a few representative examples.

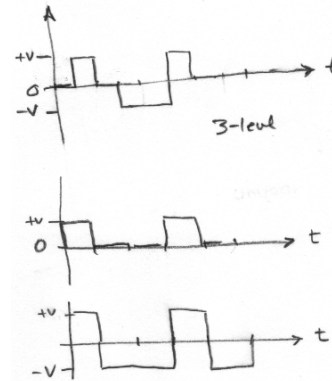
### Characteristics of Line Codes

#### Voltage Levels

Most line codes use only two voltage levels. These are the simplest to implement and have the largest noise immunity for a given transmit power.

The two voltages may be balanced about zero (sometimes called a bipolar code) or one of the levels may be zero (sometimes called unipolar).

Three-level codes are also common. A typical example is a bipolar line code that alternates a zero value and two polarities (negative and positive voltages of equal magnitude). This allows the average value of the waveform (the DC content) to be zero.



#### Transitions

Some codes allow a maximum of one transition per bit, while others allow two. More transitions per symbol typically means a higher bandwidth for a given symbol rate, but the actual spectrum will depend on the statistics of the transitions which in turn depend on the details of the line code.

Some codes guarantee a minimum number of transitions in a given time interval. This can help the re-

ceiver recover timing information that is used to recover the transmitted data.

## Differential Coding

It is possible to encode each bit as a waveform that is either different from or the same as the previous waveform. For example, with two voltage levels a data value of '1' could be transmitted as a change from the previous level and '0' as no change.

Differential encoding makes the data insensitive to the channel polarity. This is convenient since it allows cable pairs to be connected without regards to polarity.

One disadvantage of differential encoding is that errors always occur in pairs and this doubles the bit error rate.

**Exercise 2:** Assume a 1 is transmitted as 5V and 0 as 0V. Draw the waveform for the bit sequence 1011. Draw the waveform if the bits are transmitted differentially with a 1 encoded as a change in level. Assume the initial value of the waveform is 0. Invert the waveform and decode it.

## Bit Stuffing

Bit stuffing is a technique used to avoid long runs of all 1's or all 0's. The transmitter and receiver both count the number of consecutive 1's (and/or 0's) seen and if this count reaches some upper limit the transmitter inserts a bit of the opposite value and the receiver removes this extra bit.

The disadvantage of bit stuffing is that the data rate is no longer predictable because it depends on how often bit stuffing happens which in turn depends on the data values being transmitted.

**Exercise 3:** You receive the sequence of bits 10001101 and are told that bit stuffing was used to limit runs of 0 to three or fewer. What sequence is the original data sequence?

## Block Line Codes

Some line codes operate on blocks of bits. They read a number of data bits from the source and output a larger number of bits (symbols). For example, the a line coder can read a block of 3 bits bits and output 4 bits. This called a 3B4B code (B stands for binary).

**Exercise 4:** How many combinations are there of 3 bits? Of 4 bits? How many bits might be input and output by an 8B10B code? What might a 4B3T code mean?

The block code typically does not output patterns that have undesirable properties such as being all-zero or all-one, having too many more zeros than ones or a long interval between transitions.

Block codes can be more efficient because the ratio of output to input bits can be low (10/8, for example). But this comes at the cost of additional complexity for encoding, decoding and marking and detecting the boundaries of the blocks. Synchronization is usually done by using of certain output bit patterns that do not normally happen in data.

## Violations

Some line codes allow for the encoding algorithm to be violated to indicate infrequent events such as the start of a frame. A typical example is transmitting two adjacent bipolar pulses with the same polarity rather than alternating.

In other cases violation of the line coding rules indicates an error. This can be useful for detecting problems at the physical layer (we will study other techniques that are used at higher layers).

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## Properties of Line Codes

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### Bandwidth

Line codes determine the bandwidth required to transmit the signal. It is desirable to minimize the bandwidth of the baseband signal.

One reason is to maximize the symbol rate that can be transmitted over a channel with limited bandwidth.

Even when ISI due to limited bandwidth is not a concern, another reason to limit the bandwidth of signals is that higher frequencies in the spectrum of the signal radiate more easily than low-frequency components and are more likely to cause crosstalk and interference.

The spectrum of the line-coded signal depends not just on the waveforms used, but also on the sequences of these waveforms.

### Low-Frequency Content

In many cases transformers are used by baseband channels for impedance matching or protection pur-

poses. In these cases low frequencies (typically below a few 100 Hz) are greatly attenuated. For these types of channels it is useful if the line code has little frequency content at low frequencies since this will minimize distortion of the waveform.

### DC Balance

Line codes can be designed so that the average voltage of the waveform (its DC value) is zero. This is different than having low low-frequency content. For example an NRZ signal with voltages balanced about zero will have significant low frequency content but zero average voltage.

### Maximum Time Between Transitions

Digital systems use a periodic signal called a clock to synchronize the transfer of data between devices. Few communications systems transmit a clock signal along with their data. The receiver thus has to recover the clock from the received data.

both the transmitter and receiver know the clock frequencies so the clock recovery problem is limited to correcting for an the accumulated phase difference between the clocks due to the frequency difference.

Modern receiver and transmitter clocks are controlled by quartz crystal oscillators with accuracies of tens of ppm (parts per million).

**Exercise 5:** A link operates at 100 Mb/s. What is the bit period? The transmitter and receiver have independent clocks (oscillators) with accuracies of 100ppm. What is the maximum difference between the two clock periods in ppm? In seconds? The error accumulates over time. How many bits will it take for the accumulated error to equal 10% of the clock period?

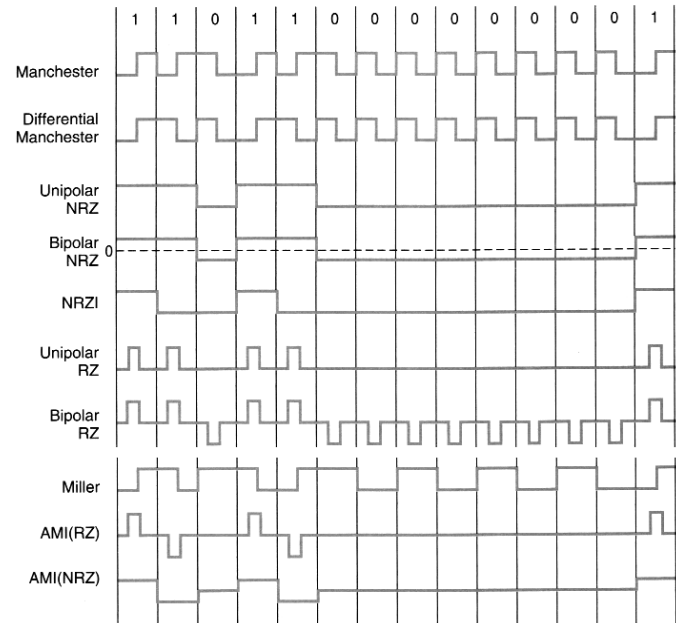
Receivers look at the transitions between signal levels to help estimate the phase error between their clocks. More signal transitions provides more information for the receiver to resynchronize its clock.

**Exercise 6:** What is the probability of having 100 consecutive 1's in a stream of random bits? How often would this happen at a bit rate of 1 Gb/s? (Hint: 1 Gb/s is about  $2^{30}$  bits/second, 1 year has about  $2^{25}$  seconds).

### Commonly-Used Line Codes

This section describes some common or representative codes. The figure below shows some of these

codes and is from the text by Hioki:



### NRZ - Non-Return to Zero

The two waveforms are two different voltage levels with durations equal to the bit period.

NRZ is the line “code” typically used between logic devices and is also used for short links. Short is short relative to the propagation time.

**Exercise 7:** A data link operates over a distance of 10m operates at 100 kb/s. If the velocity factor of the cable is 0.66, what is the propagation delay in microseconds? What fraction of the bit period does this represent?

NRZ can use differential encoding so that a 1 is encoded as a change in level and 0 is encoded by no change.

The 12 Mb/s USB protocol uses differential NRZ. A change in voltage represents a '1', no change represents a '0'. To avoid long periods without transitions a '1' bit is bit-stuffed after 5 consecutive 0's.

### RZ

The waveforms in the RZ line code return to zero in the second half of each bit interval.

The first part of each waveform (1 or 0) can be encoded as unipolar or bipolar. The first part can also be encoded differentially if desired.

RZ ensures a transition in every bit if bipolar encoding is used. The disadvantage is the increase in bandwidth.

This code is also used for 100 Mb/s Ethernet (100BaseTX).

## Manchester

A '1' is transmitted as a waveform that goes from low to high half-way into the bit period. A '0' is transmitted as a waveform that goes from high to low half-way into the bit period.

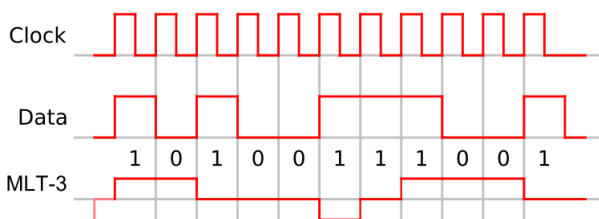
Manchester coding can also be transmitted differentially. A '1' is encoded by using the other waveform than was used for the previous bit and a '0' is encoded by the same waveform as the previous bit.

Manchester coding is used by 10Mb/s Ethernet (10BaseT).

## MLT-3

There are three voltage levels. Each '1' bit switches to the next level. When the highest or lowest level is reached the direction reverses. This produces something that looks like a sine wave and thus has a compact spectrum.

This is the line code used for 100 Mb/s Ethernet (100BaseTX). The following example is from Wikipedia:



## 4B5B

This code converts a sequence of 4 bits into a sequence of 5 bits.

Since there are 16 input sequences and 32 output sequences, certain problematic output sequences can be omitted (not used). Those sequences include those that do not have transitions and those that have more than a certain number of consecutive 1's or 0's.

The advantage of 4B5B is that only a relatively small increase in bandwidth is required while still ensuring low DC content and a minimum transition density.

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## Conclusion

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Line codes encode data bits into waveforms that are suitable for transmission over baseband channels.

The choice of line code will depend on the requirements of the application and will include compromises between bandwidth, DC content, transition density and implementation complexity.