# Physical Layer

**Lecture 3** Physical Media and Attenuation

The physical layer is about communication between adjacent nodes.
→ What signals do we send?
→ How do we deal with distortion?

Say A is sending a message to B.
(binary: $0 \mapsto 0V$, $1 \mapsto 5V$)

Ideally, B would receive exactly what A sends.
What could go wrong?
→ There could be $\underbrace{\text{magnetic flux}}_{\text{due to currents between other people talking}}$ through the circuit, $\underbrace{\text{messing up}}_{\text{emf} \propto \frac{dB}{dt}}$ the voltages.

Cross-Talk

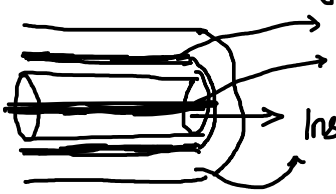
"Cross-talk"

How to fix?
- Reduce area of loop.
- Twisted-pair.  reduces flux. If done well, eliminates most cross-talk

CAT-3 cables have 10 Mbps over 100m.
CAT-5 cables have 100 Mbps over 100m.
CAT-6 cables have 1 Gbps over 100m.
10 Gbps over 50m.

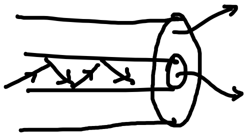
- Ethernet connectors have many wires coming in.
(8 wires — 4 twisted pairs)

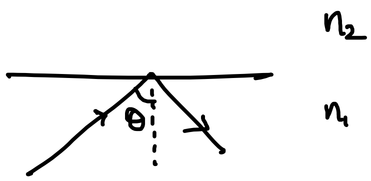
- Co-axial cables have a layer of shielding / insulation.




(0.2 in) ThinNet Coax give 100 Mbps over 200m
(0.4 in) ThickNet Coax give 100 Mbps over 500m

- Optic fibres allow very high data rate. They use $\underbrace{\text{light rays}}_{\text{fired from laser.}}$ instead of electric signals, thus reducing attenuation.




$$\theta \geq \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

Modes
Multi-mode fibre

If it allows multiple angles to pass through (modes), it is called multi-mode fibre.

They are not the best because different modes can overlap. In single-mode fibre, only one mode passes through.

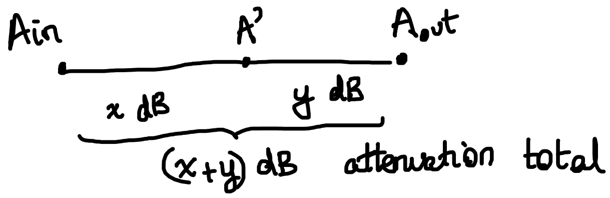
↳ Reduce diameter or increase refractive index.
More expensive.

Say A transmits amplitude $A_{in}$ and B receives amplitude $A_2$.
The attenuation, measured in dB, is equal to

Attenuation

$$10 \log_{10}\left(\underbrace{\frac{P_{in}}{P_{out}}}_{\text{Powers}}\right) = 20 \log_{10}\left(\frac{A_{in}}{A_{out}}\right).$$

It is usually measured in dB / 1000 ft instead
Note that it is additive over distance.



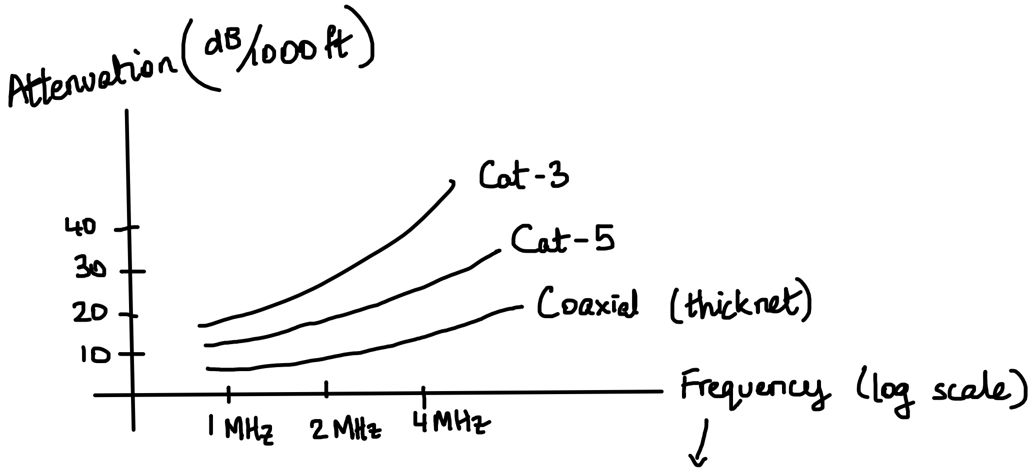

(Note that we are not taking over unit distance here.)

$$\left(\frac{A_{out}}{A_{in}}\right) = \left(\frac{A_{out}}{A'}\right) \cdot \left(\frac{A'}{A_{in}}\right)$$

If P goes to P/2, attenuation is ~3dB.

We also measure absolute power in dBm, dBW.
Suppose power P.

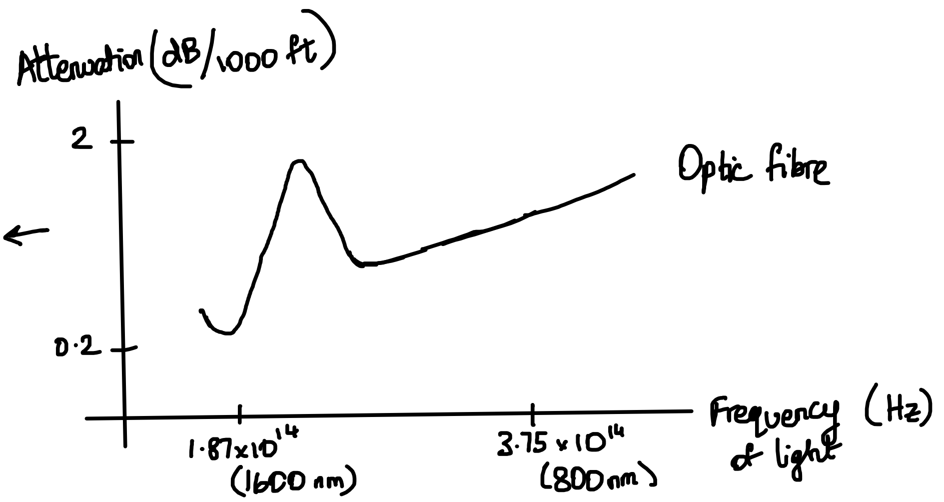
$$10 \log_{10}\left(\frac{P}{1\,mW}\right) \longrightarrow \text{Power in dBm.}$$



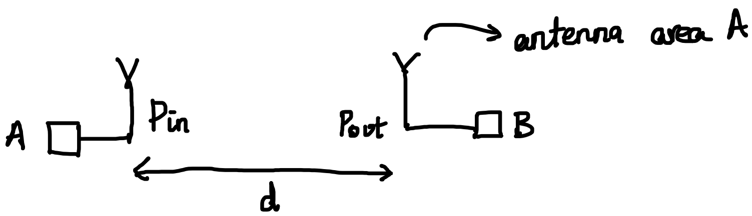

Influences inductance and capacitance

Freq ↑, Attenuation ↑

Very low! ←




Say A and B are communicating wirelessly. A sends signals via antenna.




If power is spread isotropically in all directions,

$$P_{out} \propto \frac{P_{in} \cdot A}{d^2}$$

↳ Huge power loss with distance.

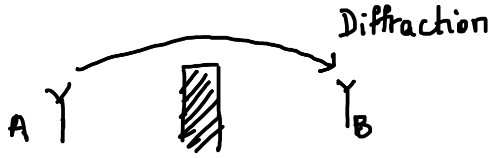
In real life, it's even worse at $d^\alpha$ for some $2 < \alpha < 5$.

To solve this, we sometimes use directional antennas. (dish antennas for example)

MIMO

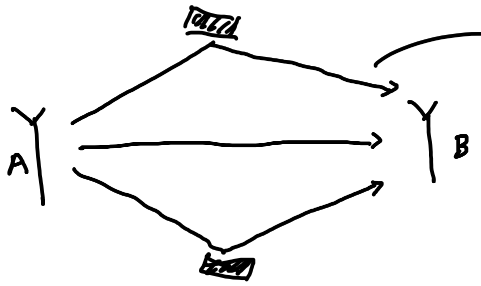
Nowadays, we use MIMO (multiple-input and multiple-output) or more recently, massive MIMO.

In the wireless case, we could have
→ Interference (counterpart of cross-talk)
→ Obstructions




(Not a problem if line of sight)

→ Multipath (counterpart of multimode)




→ This arrives later and might have significant phase difference.

Lecture 4 Line Coding

Given a set of bits, we have to convert them into signals. How?

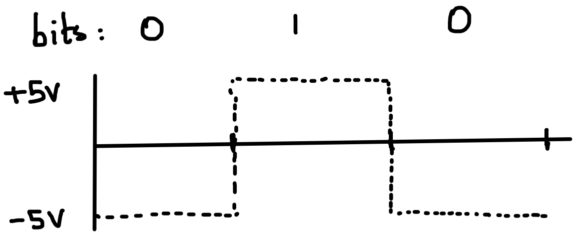
Wired situation.

Line Coding

We use line coding.

- Non-return to zero (NRZ)

NRZ




→ Negative voltage.

(+5V when 1 and
-5V when 0)

Issues with NRZ:

- Clock recovery - 001100 and 010 are essentially the same
  How would we infer the actual clock duration of the sender?
  The clock may be slightly slower/faster due to imperfections and may also have "drift".
  ↳ getting slower/faster with time
  We are unable to recover the clock from the signal.

Clock recovery

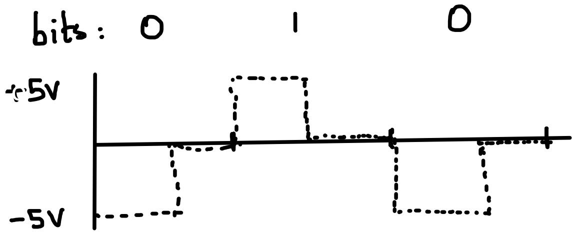
- Baseline wander - Instead of being exactly −5 and +5, there may be some offset. The DC offset is the average of the two offsets - the "new 0". This leads to errors other than the usual errors itself.

Baseline Wander
DC Offset

If we use a high pass filter, it partially resolves it.
However, if there is a long string of 0s or 1s, it gets messed up.

- Return to Zero (RZ)

RZ



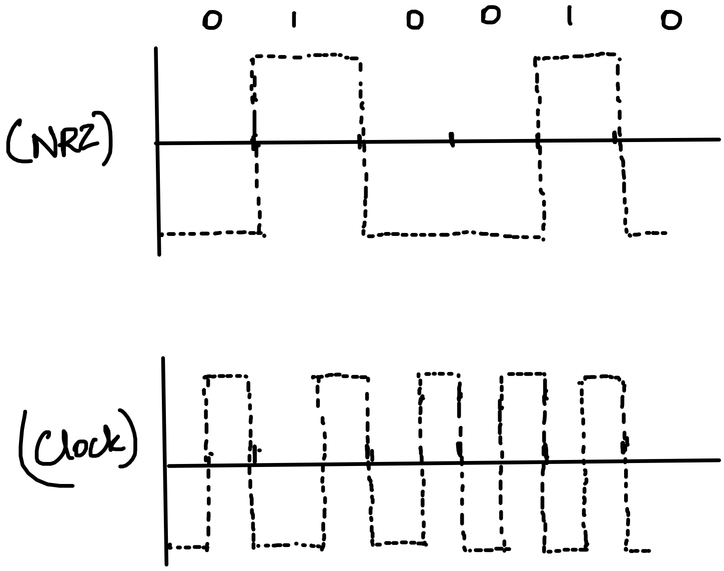

(Return to 0 at the middle of each bit)

We never have a constant signal for a long time, so high pass filters can remove baseline wander.
However, the issue is that we now have three levels.

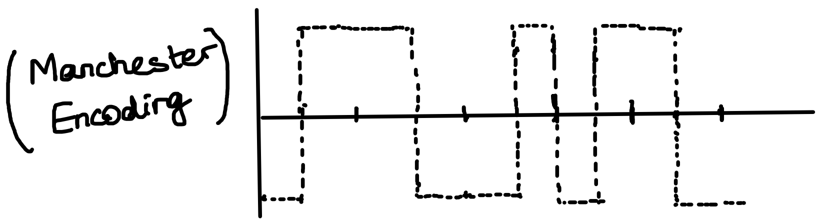
- Manchester Coding (802.3 IEEE)
  ↳ standard for ethernet

Manchester Coding

This is what is used usually.
We start with NRZ.




We then XOR the two.



The regular transitions eliminate the issue of clock recovery.
Like RZ, we can use a high pass filter to eliminate baseline wander.
(but only two voltage levels)

Note that the encoding of a 0 has a positive transition
1 has a negative transition

We can recognize the bit if we know where it starts.

1. We need to know where each bit begins.
2. We mustn't mess up the polarity.

To do 1, we use a known signal known as the preamble to synchronize. Before the actual message, we insert this special signal. It can be thought of as a physical layer header.

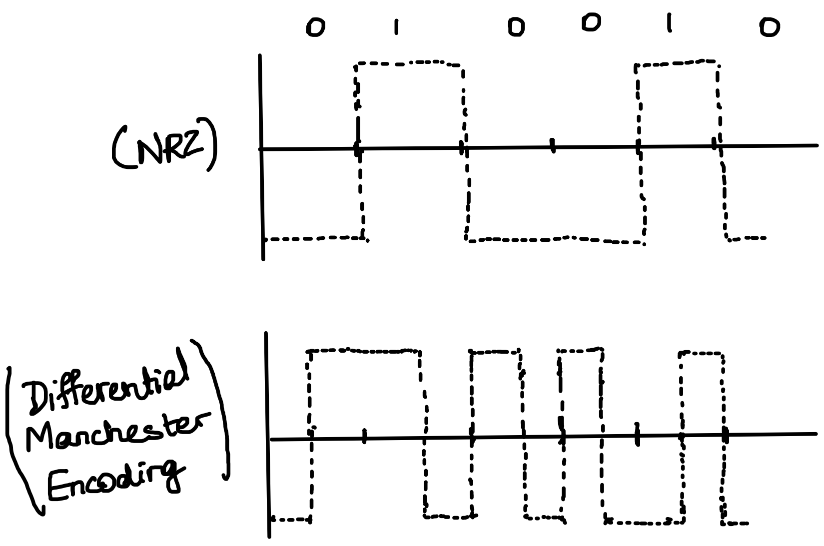
Differential Manchester Encoding

- Differential Manchester Encoding (802.5 IEEE)

It is used in token ring LANs (see. DLL)

For a 0, the first half is opposite of the last half of the previous bit.
1, the first half is equal to the last half of the previous bit.

Within each bit, there is a clock-like signal.




This has the advantages of Manchester encoding and further, the polarity issue is now gone.
(just see if it inverts or stays the same)

- **4B/5B Encoding:**

Recall that in NRZ, we run into issues if the same bit occurs multiple times.

4B/5B Encoding

What if we manually change it once in a while?
What this does is that for an input of 4 bits, it gives out 5 bits. For example,

0000 → 01010
1000 → 10010
⋮
$2^4$ such things.

This ensures that there are atmost 3 consecutive 0s/1s in the encoded bit string.
This is disadvantageous because there is some degree of redundancy.

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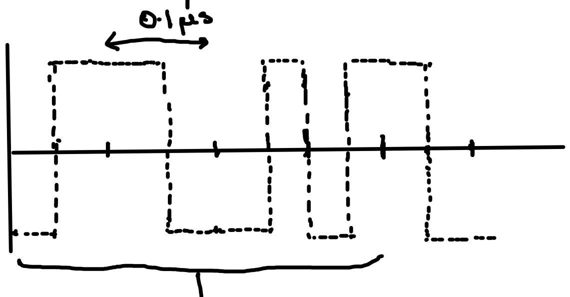
**Baud Rate:**

Recall that the bit rate is the maximum possible number of bits transferred per second.
The Baud rate is the maximum allowable number of symbol changes made to the transmission medium per second.

Baud Rate




for example, 5 symbol changes
Worst case, one change every 0.05 μs
↓
Baud rate = $2 \times 10^7$ symbols $s^{-1}$

In some sense, Baud rate captures what potential we can use the medium to
The allowable frequency range is related.
↳ recall that as freq.↑, attenuation ↑.

An allowable signal should have most of the Fourier transform contained within the allowable frequencies.

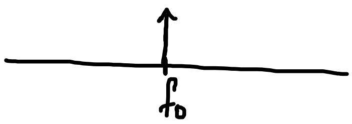
Observe that in Manchester, Baud rate > bit rate and → twice as much
in NRZ, Baud rate = bit rate.

## Lecture 5 Modulation in Wireless Networks

Suppose we have a sender with an antenna. He wants to send a signal.
How would he do that? A free-for-all is infeasible.
The government steps in.
They auction certain ranges (→ spectrum) of frequencies for explicit purposes.
Then even if different frequencies interfere, we can use a bandpass filter.
Some bands like WiFi are unlicensed, but then interference is not an issue.

Say we are limited to $(f_0 \pm 10\,\text{MHz})$

$\cos(2\pi f_0 t) \xrightarrow{\text{F.T.}}$




But doesn't convey any information.

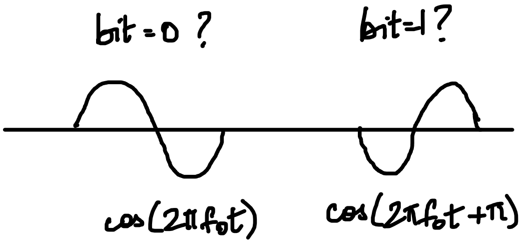
This is where modulation enters the picture.

Carrier wave : $\cos(2\pi f_0 t)$

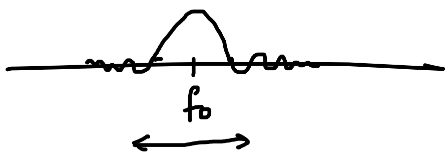
$A \cos(2\pi f_0 t + \theta)$

Amplitude Frequency Phase → 3 types of modulation.

(F.M. used in analog)




You can show that the Fourier transform looks something like




Width depends on how frequently you change phase.
↳ Usually for more than just 1 wavelength

If we change less frequently, low rate of transmission but restricted to a narrower band.

Say $s(t)$ is transmitted and

due to reflections                noise

$$r(t) = \sum_{i=1} a_i \, s(t-\tau_i) + n(t)$$

attenuation    delay    if added, "additive white gaussian noise" (AWGN)

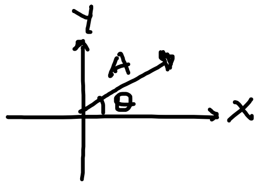
(most general case)

is the received signal.

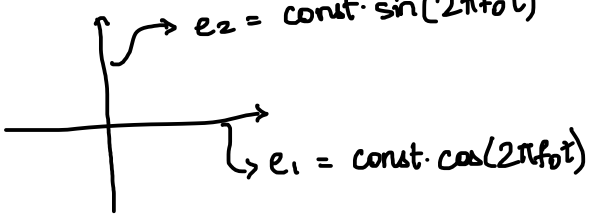
The bit error rate is the fraction of transmitted bits received erroneously.
(interpreted)

Bit error rate

We can think of signals in a vector space.
Focusing on frequency $f_0$, we can represent a wave $A\cos(2\pi f_0 t - \theta)$ by the vector of magnitude $A$ at angle $\theta$. (in $\mathbb{R}^2$)




What would be the equivelent of the dot product here?




In these functional vector spaces, the inner product of square-integrable functions $f, g : [0,T] \to \mathbb{R}$ is

$$\langle f, g \rangle = \int_0^T f(t) g(t) \, dt$$

If we send the signals over time $T = N/f_0$,

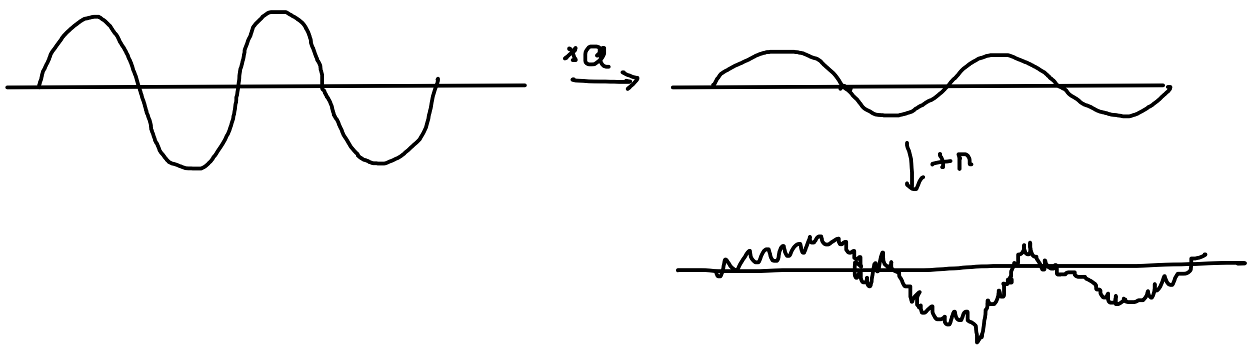
since $\langle e_1, e_1 \rangle = \langle e_2, e_2 \rangle = 1$,

$$e_1 = \sqrt{\frac{2f_0}{N}} \cos(2\pi f_0 t) \quad \text{and} \quad e_2 = \sqrt{\frac{2f_0}{N}} \sin(2\pi f_0 t)$$

and $\langle e_1, e_2 \rangle = 0$.

Suppose $r(t) = \underbrace{a}_{\text{attenuation}} \cdot s(t) + \underbrace{n(t)}_{\text{AWGN}}$

$$r_x = a\langle s, e_1 \rangle + \overbrace{\langle n, e_1 \rangle}^{n_x}$$
$$r_y = a\langle s, e_2 \rangle + \underbrace{\langle n, e_2 \rangle}_{n_y}$$

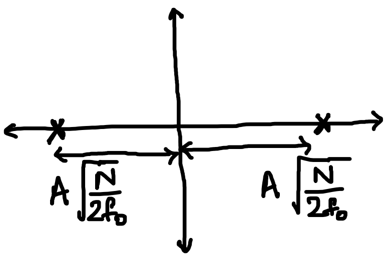



$$g = A\cos(2\pi f_0 t - \theta) = \frac{A}{\sqrt{2f_0/N}} \left( \cos\theta \, e_1 + \sin\theta \, e_2 \right)$$

Suppose we transmit $s(t) = A\cos(2\pi f_0 t)$ if bit 0

$s_1(t) = -A\cos(2\pi f_0 t)$ if bit 1

for time $0 \le t \le T = \frac{N}{f_0}$.

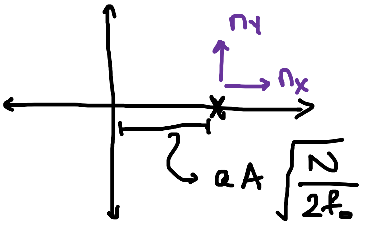


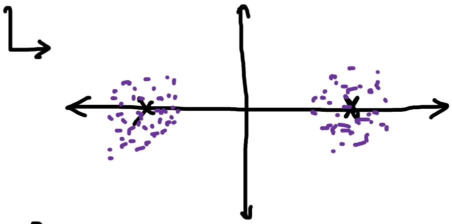

↳ Constellation Diagram

Say bit 0, so $s(t)$. We receive $as(t)+n(t)$

$$r_x = as_x + n_x$$

AWGN $n$ is such that $n_x$ and $n_y$ are iid Gaussian.



(If we transmit the same bit several times)

Looks like a constellation.

How do we do detection?

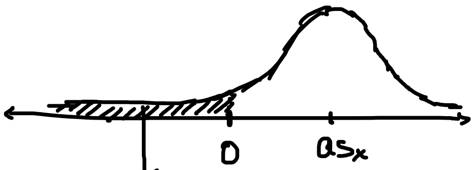
Say $r(t) = a\,s(t) + n(t)$

→ Calculate $r_x$ and $r_y$.

→ Find the constellation point closest to $(r_x, r_y)$.

(In this example, just see if $r_x > 0$ or $r_x < 0$)

$r_x > 0$ → bit 0; $r_x < 0$ → bit 1




This tail probability is the probability of interpreting it incorrectly (if 0 is transmitted)

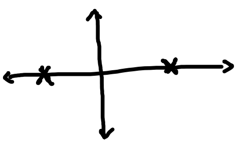
The signal-to-noise ratio (SNR) is the ratio of signal power to noise power.

Signal-to-noise ratio (SNR)

The above modulation scheme is known as Binary Phase Shift Keying. (BPSK)

BPSK

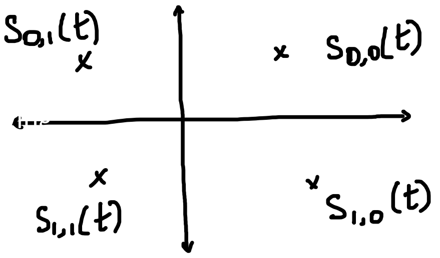
(180° out of phase)



could switch 0 and 1 or even keep them on Y-axis.

In Quadrature PSK (QPSK),

QPSK

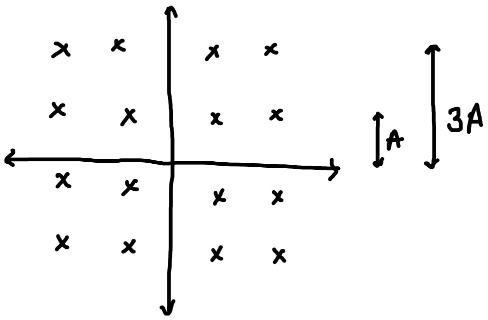



Can send two bits of data at a time.

Transmission /detection is nearly identical to BPSK.

In QAM-16,

QAM-16




Four bits of data at a time

QAM-256 has 8 bits of data.

QAM-256

What constellation do we use?

1. Allowed transmit power
2. Received signal power

Bit Error Rate is a function of SNR.

Say QPSK vs QAM-16 with same received signal power (and same attenuation).

QPSK ↓ Slower but lower BER

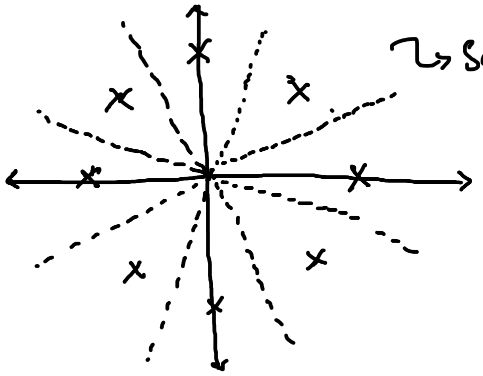
QAM-16 ↓ Faster but higher BER

For example, our WiFi card constantly sees the SNR and dynamically changes the scheme used.

 Modulation (contd.)

Each of these x's in the constellation diagram is called a symbol
The transmitted signal is just the concatenation of the signals corresponding to each of the bits.
8-PSK is

Symbol
8-PSK



↳ Sectors according to which we decide what to interpret received signal as.

QAM-16's sector division is slightly trickier (what is it?)
(and not even uniform, in fact)

PSK is convenient because amplitude doesn't even enter the picture.