The Physical Layer

COMPUTER NETWORKS A.A. 24/25

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Program Reference

- Only the final part of these slides are taken from the book, however the slides are licensed under a Creative Commons Attribution-Share Alike 3.0 Unported License.
- What is **required** as part of the exam program are:
  - A general understanding of the principles
  - All the definitions:

    Def: This is a definition

  - The exercises at the end of the lesson

Sect. 1 The Physical Layer

Bit-rate

bit-rate: The speed of a communication link, expressed in bits per second

- The standard unit of bit-rate is indicated as bit/s or b/s, colloquially this becomes 'bs'
- One Mbps is one million bits per second and one Gbps is one billion bits per second. This is in contrast with memory specifications that are expressed in Bytes (8 bits), KiloBytes (1024 bytes) or MegaBytes (1048576 bytes).

bit Rate	bit per second	Example
1 Kbp/s (Kbps)	10^3 b/s	Traffic of an IoT device
1 Mbp/s (Mbps)	10^6 b/s	Decent 3G/4G data connection
1 Gbp/s (Gbps)	10^9 b/s	Fast FTTH home fiber connection
1 Tbp/s (Tbps)	10^{12} b/s	Transoceanic fiber connection

Transmitting bits

- What influences the bit-rate of a communication link?
- We need to dig a little into physics to understand it.

The Physical Layer

↳1.1 Notions of Physics

Work

- In physics the concept of *work* represents the result of the application of a force along a certain distance.
- Informally, *work* is *the measurable effect of your interaction with the system around you*.

Energy

- When doing work you change the energy of the objects that receives the force, so work can be seen also as a variation of energy.
- Energy can take many forms, but the its simplest form is kinetic energy (KE), that depends on the speed of an object:

$$KE = \frac{1}{2}mv^2$$

- If you take an object of mass *m* that is still, and you accelerate it till it takes speed v, you did *work*, and the *work* is exactly the difference between the KE at speed v and the KE at speed zero.

Example:

Your car accelerates from zero to 100 km/h: the engine did *work*, increasing the energy of the car

Joules

- As force is measured in Newtons and distance in meters, Energy is measured in Newton-meters, called **Joule (J)**.
- A Joule is a small quantity of energy, enough to lift a 100g object of 1 meter. We normally deal with k/MJ (kilo/mega) in mechanics but we deal with mJ (milli) in communications.
- Energy never vanishes, it is transferred from one body to another.

Power

- Power is energy per second, and it tells how fast a system can provide energy.
- Power is measured in Watt (W), that is: J/s (Joules per second)
- The KE of the car of 1000 kg at 100 km/h is 392kJ
- If the car reaches 100km/h in 10 s, the engine power is $\frac{392kJ}{10s} = 39.2kW$.
- If it takes only 3 seconds, the engine power is $\simeq$ 130kW

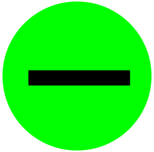
Panda

Max Power: 51-66kW depending on the asset. 0-100 km/h in 11-15s

Bugatti Chiron

Max Power: 1.1MW. 0-100 km/h in 2.4s

Charge

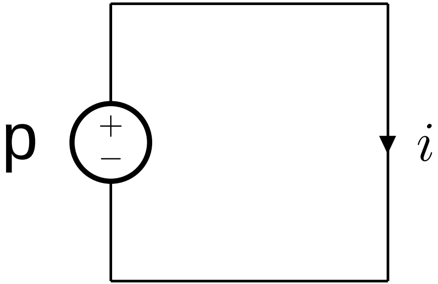


- An electron is a particle with a negative charge.
- An electron has a mass, so when it moves, it has kinetic energy.

Electric Current

- Electrons can move inside matter this is called *electric current*: Materials in which electrons can move are called conducting materials, while in isolating materials electrons can not flow freely.
- Current is measured in Coulomb/s, called *Ampere*. 1 Ampere is a relevant current, so often mA are used (consider, 50mA is the threshold of pain).

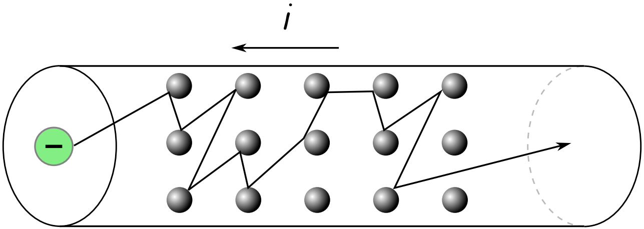
Power and Current



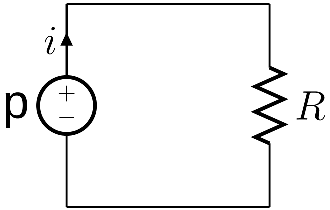
- A current generator "*pushes*" the electrons in the wire. Electrons pass from zero speed (not really true, but let's assume it) to a certain speed, so the generator gives electrons some energy.
- To accelerate 1 electron, the generator consumes a certain amount of energy.
- To accelerate many electrons for some time t, the generator **consumes power**.
- In the figure there is an electric circuit, with a generator that consumes a power of *p* Watt

Resistance

- When electrons move in a certain material, they don't go *straight*
- They bounce against the structure and they lose some energy, which is transferred to the material, their kinetic energy is transformed into heat
- We say materials offer a certain Resistance to the current.

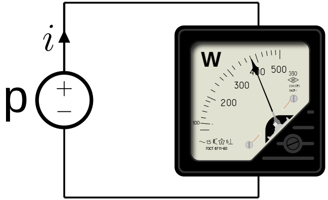


Circuits



- In the figure you have a circuit made of a generator and a resistance.
- The generator puts power **p** into the circuit, the power is transformed into a current.
- The resistance dissipates the power, for instance, heating up.

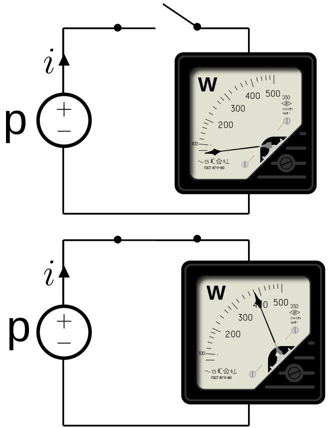
Measuring Pwer



- You can use a device to measure if there is current in the circuit.
- The device has a *sensitivity*, if the received current is higher than a certain threshold, it measures some power

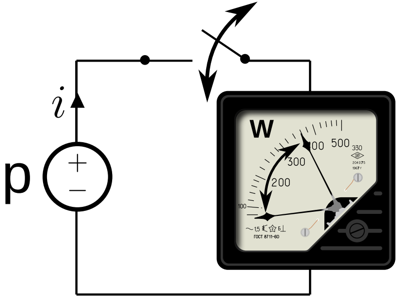
Sensitivity: The minimum amount of power that the sensor needs to receive to sense the presence of the current.

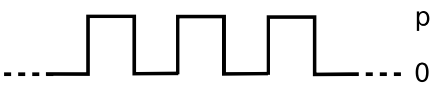
A switch



- Let's add one last component: an on/off switch. This simply disconnects the circuit and prevents current to pass.
- If the switch is off (top figure) then the current is zero and there is no measured power
- If the switch is on (bottom figure) then the measured power is not zero

A Signal

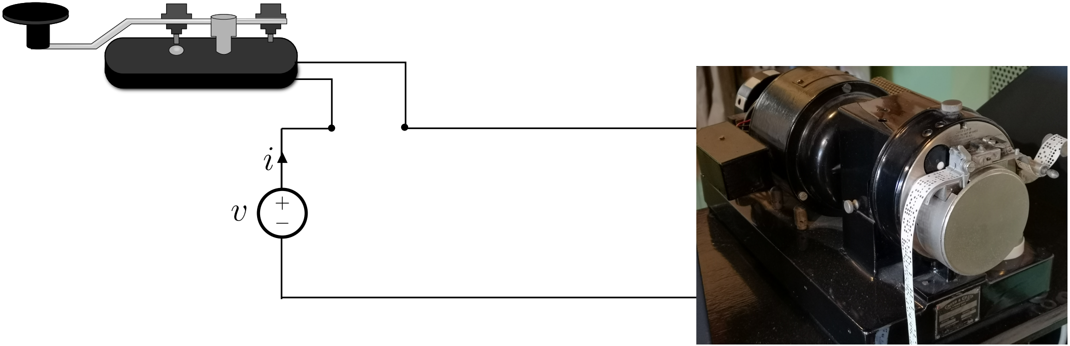




- Now imagine that you periodically switch on and off the switch, with a 1 second period.
- Imagine also that instead of just watching the sensor, you plot its value.
- Congratulations: you created and transmitted a clock signal!

Telegraph

A telegraph uses this principle.

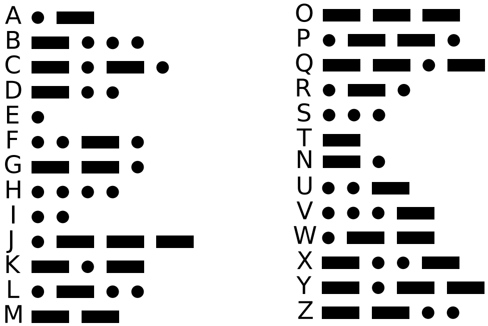


Encoding Information: Morse Code

- The telegraph used to transmit Morse code, i.e. a sequence of long-short symbols that matched the English alphabet

International Morse Code

1. The length of a dot is one unit.
2. A dash is three units.
3. The space between parts of the same letter is one unit.
4. The space between letters is three units.
5. The space between words is seven units.

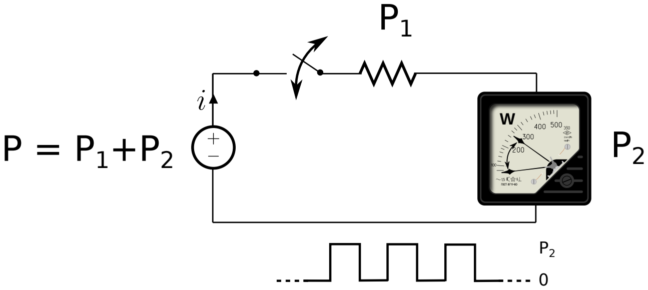


The Physical Layer

↳ 1.2 Attenuation and Noise

Attenuation

- The copper cable has a certain resistance which is never zero.
- Part of the power is lost in the cable, the longer the cable, the higher the lost power.
- So to be precise, the real scheme of the circuit is the following one:



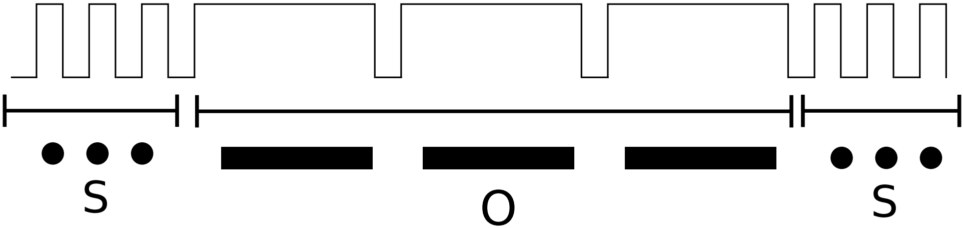
Attenuation

Attenuation: Part of the power that the generator introduces in the circuit is lost, due to the resistance of the circuit itself. We call this effect attenuation. A longer cable has a higher resistance, so, the higher the distance between source and receiver, the higher the attenuation.

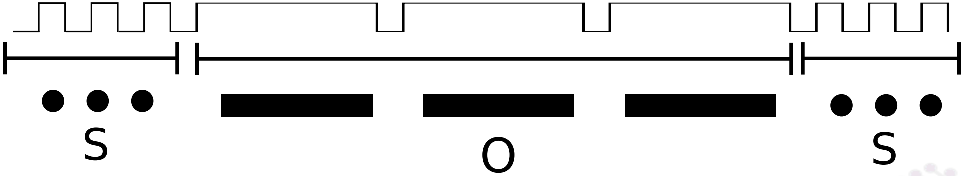
As a result, the shape of the received signal is the same, but its amplitude is lower: You need a sensor with a higher sensitivity!

Attenuation

Transmitted signal



Received Signal



Attenuation per meter

- The attenuation depends on the type of cable (material, size) and on its length, and the communication frequency (more on this later)
- Normally it is given as a fractions of W lost per m, or per km
- For example, a copper cable can reduce the power to $\frac{1}{25}$ per km
- This means a factor of $\frac{1}{25^2}$ in two km and so on…(see exercise at the end of the lesson).
- Note, this is not a linear decay, it is much faster.

Delay

- Electrons (or any other mean we use to communicate) do not travel at infinite speed
- The signal takes some time to travel from one place to another
- The receiving end needs to detect the beginning and the end of each symbol

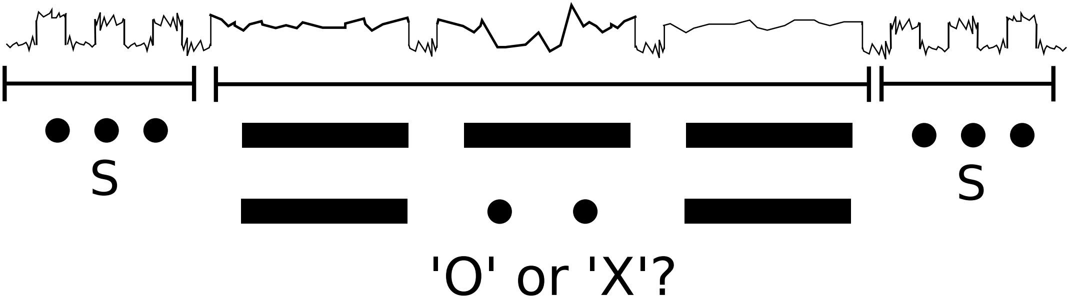
Delay (link latency): The time it passes from when the signal transmission starts at the sender and when it is started to be received at the receiver.

Noise

- Electrons are never still, if not at zero Kelvin degrees. At normal temperatures they keep moving.
- So ideally, there is never zero current in the circuit.
- So even in the *off* position, the sensor measures a small, randomic signal. This is called Thermal noise.
- As a result, every communication is made of a signal, summed to some noise.
- Besides thermal noise, there can be other forms of noise, coming from other devices interfering with the communication.

Noise

When you have a signal that is attenuated, and mixed with noise, you can have errors decoding it:



Signal to Noise Ratio (SNR)

- From the previous example we can see that the device that decodes the signal and transforms it into digital information receives both the signal and the noise together
- The difference must be clear enough to distinguish the signal from the noise.
- In formal terms we call

SNR:

$$\text{SNR} = \frac{\text{Power of the received Signal}}{\text{Power of the Noise at the Receiver}}$$

Signal to Noise Ratio (SNR)

- SNR can be measured on Energy, or on Power received, and averaged on a certain period.
- It always refers to what the receiver radio measures.
- So it depends on the transmitted power, the attenuation and the noise at the receiver: these are elements of a **communication link**.
- The SNR is the fundamental characteristic to estimate the performance of a communication link.

Take Away: sensitivity, attenuation, Synchronization

Sensitivity: Every receiver needs to receive a minimal power to even notice that there is a signal. Below the sensitivity level, the receiver does not detect any input signal

Attenuation: Every signal transferred over any communication channel loses some of its initial energy, so the received power is less than the transmitted one

Delay (link latency): The time it passes from when the signal transmission starts at the sender and when it is started to be received at the receiver.

Take Away: Distance Matters

- The longer is a cable, the more you have two negative effects:
  - Higher attenuation: this means less received power, that means the signal is harder to decode
  - Higher delay: the time it takes for the bit to reach the destination is higher

Take Away: Noise, SNR

Noise: In every real world communication (not ideal) the signal is mixed to some noise. There are many sources of noise, including thermal noise. We care only about the noise at the receiver radio.

SNR: If the received power is higher than the sensitivity of the receiver, the capacity to correctly decode the data depends on the SNR: the ratio between the energy of the signal and the energy of the noise. The higher, the better.

Properties of Each Component

- The **radios** have some fixed properties: The maximum transmission power, the sensitivity.
- These two properties can not change unless you don't change the radio
- The **communication channel** has some properties: the power attenuation (that depends on the distance) and the noise level at the receiver.
- If you use a different cable or repeat the test in a different environment (with more or less noise) the performance will change.
- The **SNR** is thus a property of the **link**: radios, channel (cable), noise conditions.

The SNR influences the link bit-rate in b/s. The higher the SNR, the higher the maximum bit-rate.

One last definition:

Synchronization: The receiver and the sender need to agree on when a certain symbol begins and when it ends, so they need to agree on the duration of each symbol (that is generally a constant)

- The delay does not directly influence the link speed.
- You can have a 100mb/s link with 1ms delay, or with 1s delay.
- We will see that however, it indirectly affects the throughput, that is, the fraction of the bit-rate you can actually use to send data.

The Physical Layer

↳1.3 Modulation

Sending Signals

- Ideally we would like to always send the digital signal as shown so far
- Instead, for reasons we can't go deep into (just ask if you want more) we never do that
- We use *modulation*

Modulation

Modulation: In a modulated signal you have:

- a Carrier signal: normally a sinusoid with frequency f_c (frequency is expressed in Hertz, that is $1/$seconds)
- a modulating signal: the signal you want to transmit

The key idea of modulation is to affect the amplitude, frequency or phase of the carrier sinusoid to encode the information that represents the modulating signal, and obtain a *modulated signal*.

FM

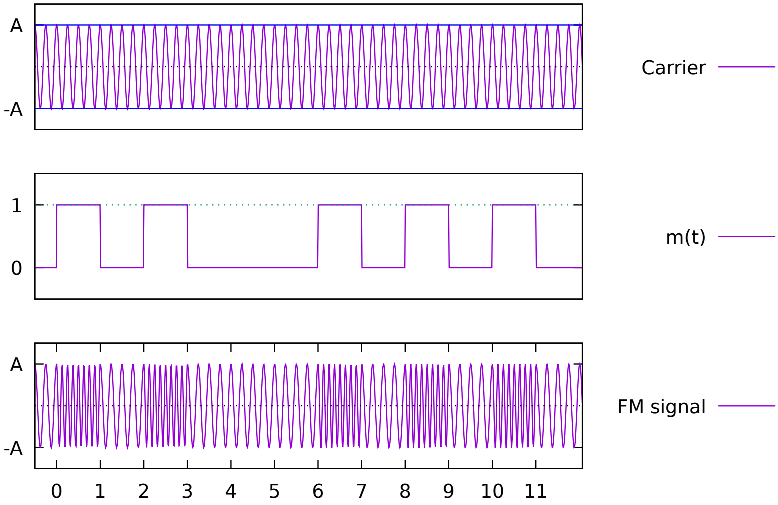
Frequency Modulation (FM):

- We have a carrier $p(t) = Acos(2\pi f_p t)$, and a digital signal $m(t)$ to be transmitted
- We can modify the frequency of the carrier incrementing it of a value Δ:

$$\begin{cases} f'_p = f_p & \text{if } m(t) = 0 \\ f'_p = f_p(1 + \Delta) & \text{if } m(t) = 1 \end{cases}$$

- This makes it possible to communicate a binary digital signal, using two levels for the digital signal.

FM



What do we modulate?

- In the electronic circuit we can replace the generator of direct current with a generator of alternate current (AC/DC, as the rock band). This will create the carrier signal.
- In a wireless communication instead, there is an electromagnetic wave that oscillates, and provides a carrier

Bit Rate

- What is the bit rate of that communication?
- Let's assume $f_p = 4 \rightarrow$ 4 oscillations in one second
- Let's say that the length of one bit is determined by 4 oscillations, like in the figure. This is called a *symbol*.
- We send one symbol per second, this is called a *Baud rate* (Bd)
- Every symbol represents one bit: **the bit-rate is 1 b/s**

The bit-rate is given by the Baud rate times the bit per symbol

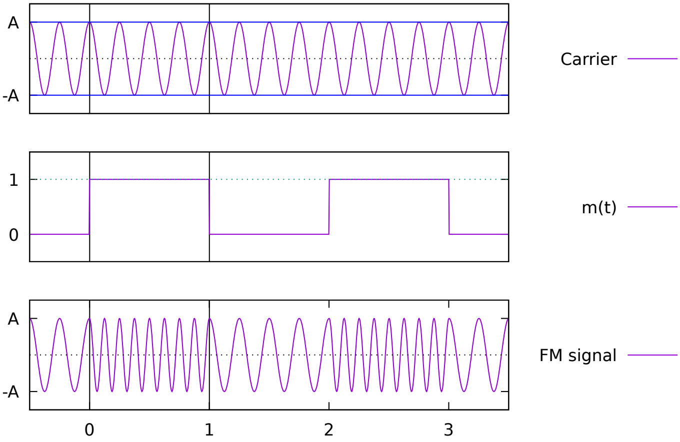
Question

How can I increase the bit-rate?

1. Reduce the length of a symbol (increase the Baud rate)
2. Encode more than one bit in each symbol

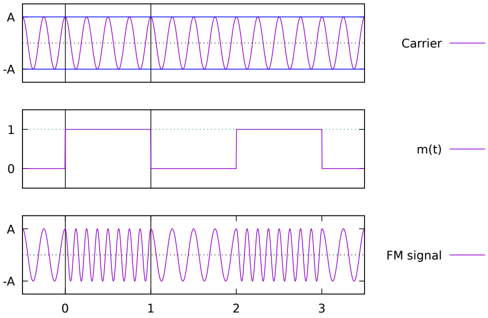
1) Reducing the Symbol Duration

- Let's zoom in the previous image



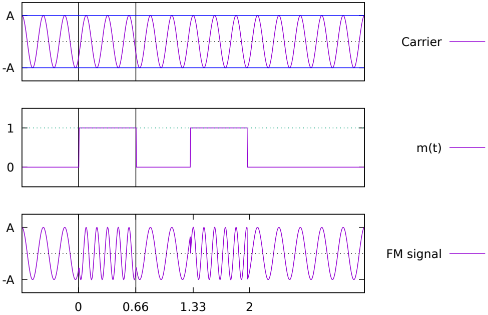
1) Reducing the Symbol Duration

- $f_p = 4$ Hz
- One symbol takes 4 oscillations: one symbol $= 1$s. Three bits: 3 seconds.
- We could use just two oscillations, then the same signal would need only 2 seconds
- This means increasing the Baud rate

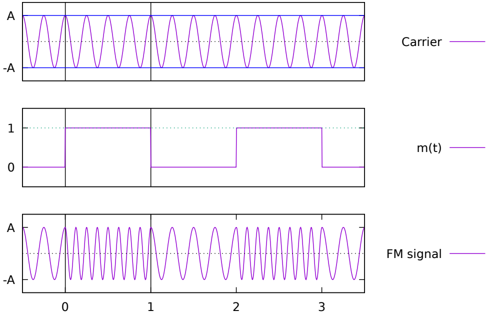


1) Reducing the Symbol Duration

1.5 symbol per second (1.5 Bd)



1 symbol per second (1Bd)



Drawback:

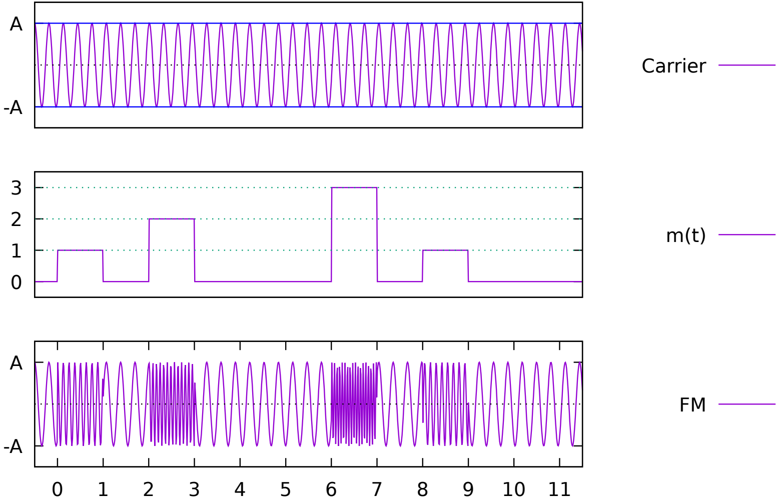
- If we increase the Baud rate we increase the bit-rate, however. . .
- it is also intuitive that the longer is a symbol, the easier is for the receiver to distinguish it from noise.
- If the symbol is shorter, it is harder to detect in noisy channels

2) Encode more than one bit in each symbol

- Use not only two levels, but a higher number M, and thus M different frequencies.
- With M=4 we have:

$$\begin{cases} f_p' = f_p & \text{if } m(t) = 00 \\ f_p' = f_p(1+\Delta) & \text{if } m(t) = 01 \\ f_p' = f_p(1+2\Delta) & \text{if } m(t) = 10 \\ f_p' = f_p(1+3\Delta) & \text{if } m(t) = 11 \end{cases}$$

FM encoding with M=4 (2 bits per symbol)



Multi-bit Encoding

- The Baud rate is the same as in the previous example
- However, each symbol carries 2 bits: **we double the bit-rate**
- Ideally, we can encode an arbitrary number of bits.
- If the receiver is good enough, and it is able to sense the difference between the frequencies we can always increase the bit-rate.

Bandwidth:

Bandwidth: The interval between the lowest and the highest frequency you use for the communications.

If you want to increase the bit-rate, you need to increase the bandwidth. This example gives an intuitive (albeit not formal) justification of this concept.

Radio limitations

- However, your radio has technological limitations
- A radio can not work at any frequency, it has a range of frequencies it can work on
- So you can't work outside those boundaries
- Also, the radio has a sensitivity when distinguishing between frequencies.
- This means you can not reduce Δ as much as you want.
- These technological limits will practically cap your bit-rate.

In the wireless domain:

! **You can not use the same frequencies for more than a communication at the same time. If you increase the bandwidth you occupy more spectrum. Frequencies are allocated by law.**

- The Wi-Fi network uses the frequencies between 2401-2483 MHz (and others)
- The 4G cellular network uses (among others) 703-748, 832-862, 880-915 MHz
- Digital TV uses 470-694MHz
- MHz stands for mega-Hz: millions of oscillations per second.

Sect. 2 Fundamental Theorems

Nyquist Theorem: a Fundamental Result

Nyquist Theorem:

- Nyquist theorem says that if your communication uses a bandwidth B, and,
- you use M discrete levels then the **theoretical maximum capacity** of the transmission in bit/s C is:

$$C = 2B \log_2(M)$$

- Note: M is generally a power of 2

Exercise:

- A link uses frequencies that range from 2401 MHz to 2441 MHz
- It uses M = 4 levels .
- What is the maximum bit-rate?

$$B = 2.441.000.000 - 2.401.000.000 = 40.000.000$$

$$C = 2Blog_2(4) = 2 * 40.000.000 * 2 = 160Mb/s$$

Exercise (2):

- A link uses frequencies that range from 2401 MHz to 2441 MHz
- The link must support 300 Mb/s
- What is the minimum required number of levels M?

$$B = 2.441.000.000 - 2.401.000.000 = 40.000.000$$

$$C = 2Blog_2(M) = 2 * 40.000.000log_2(M) > 300.000.000$$

$$\rightarrow M > 2^{\frac{300}{80}} > 13.45$$

- However, M must be a power of 2, so we must set $M = 16$
- So to have 300Mb/s you will actually provide 320 Mb/s

What about Noise?

- The Nyquist theorem completely ignores noise.
- However, we know that noise will make the reception of the bits harder.
- There is another fundamental law that we need to know

Shannon Theorem

- Shannon Theorem introduces a hard limit on the capacity (bit/s) of a signal with some assumptions on the kind of noise.
- It says that:

Shannon Theorem: The capacity of a channel of bandwidth B affected by an additive gaussian white noise is given by:

$$C = B \log_2 \left(1 + \frac{S}{N}\right)$$

- S/N is the signal to noise ratio (SNR, power or energy)

Extremes

- Consider the case in which $S \to \infty$, then $C \to \infty$. This means that if you have infinite energy you can theoretically transmit infinite information
- If $N = S$ this means that at the receiver the signal power is the same of the noise. Then $C = B$, you can still communicate information. Note that it does not matter how strong is the signal, it always depends on the ratio S/N.
- Note also you can communicate even if $S < N$.
- If $S \to 0$, for instance if you move far away from a wireless transmitter, or if $N \to \infty$: then $C \to 0$

Capacity grows slowly

- Note that the log_2 function grows slowly, way less than linearly
- This means that if you want to double the capacity, you have to increase the SNR of a power of 2:
- Example: if SNR is 255 then $C = Blog_2(256) = B * 8$, if you want to double it, you need $SNR = 65535 > 255^2$

Shannon Vs Nyquist

$$C_N = 2B \log_2(M)$$

$$C_S = B \log_2 \left(1 + \frac{S}{N}\right)$$

- Nyquist Theorem operates in an ideal world in which there is no noise and the receiver is perfect (any signal with more than zero power is received). In that case capacity depends only on B and M.
- Shannon Theorem is tighter. It says that given a certain S/N and a certain B, you simply **can not** achieve more than C, even if Nyquist allows it.

Shannon Vs Nyquist

- When S/N decreases, the receiver has more and more difficulties in distinguishing noise from signal.
- The signal must then carry less information, so it is easier to decode.
- Practically speaking, if you have a given S/N **you can not have an arbitrary amount of levels M**. The SNR determines the maximum number of levels, so the best encoding you can use.
- Note that B, S, N are given for a certain link, but the transmitter can choose M. However, M must be chosen so that $C_N \leq C_S$.

Exercise: let's put all thing together

- A wired ADSL communication can be described by these numbers:
  - Transmission power of your router: 100mW (mW $= 10^{-3}$W)
  - Noise: 0.0001 mW
  - Attenuation: the power is divided by 25 at every km
  - Bandwidth: assume 2.2MHz
- What is the maximum achievable bit-rate at 2 km considering noise?
- What is the best modulation we can use (the highest value of M)?
- What is the highest bit-rate achievable with that modulation?

Solution

- After 2 km the signal power is reduced to $\frac{100}{25*25} = 0.16\text{mW}$
- The SNR is then $\frac{0.16}{0.0001} = 1600$
- We apply Shannon's law:

$$C_S = 2.200.000\ log_2(1 + 1600) \simeq 23Mb/s$$

What Modulation?

- Let us consider only modulations that are powers of two (2,4,8...)
- We need to answer the question, what is the highest modulation we can use so that

$$2Blog_2(M) \leq C_S?$$

- Then we need to invert the Nyquist formula:

$$C_S = 2Blog_2(M) \rightarrow \frac{C_S}{2B} = log_2(M) \rightarrow 2^{\frac{C_S}{2B}} = M$$

and we have:

$$M = 2^{\lfloor \frac{23.000.000}{4.400.000} \rfloor} = 2^{\lfloor 5.227 \rfloor} = 32$$

note $\lfloor x \rfloor$ is the largest integer lower than x, so we rounded M to the closest power of 2. However this reduces the bit-rate:

$$C_N = 2Blog_2(M) = 2 * 2.200.000 * 5 = 22Mbit/s < C_S$$

What if we use a larger M?

- Let's say we set $M = 6$, Nyquist theorem says that we can achieve:

$$C_N = 2 * 2.200.000 * 6 = 26.4Mb/s$$

- However, we know that the maximum bit-rate is 23Mb/s.
- This means in average 3.4Mb/s of traffic will contain errors: 1 turns into 0 and vice versa.
- We need to re-transmit these bits, and this will reduce the useful bit-rate.
- Moreover, **errors are randomly distributed**, so we don't know what bits we need to re-transmit.

Conclusion: It makes no sense to transmit at a speed that is higher than the Shannon limit. M must be chosen so that the achievable Nyquist rate is lower than the Shannon Capacity ($C_N \leq C_S$).

Sect. 3 Extra Slides

Extra Slides

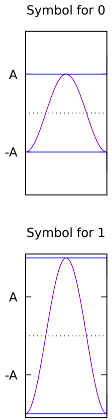
- What follows is out of the program, just helps solving some doubts.

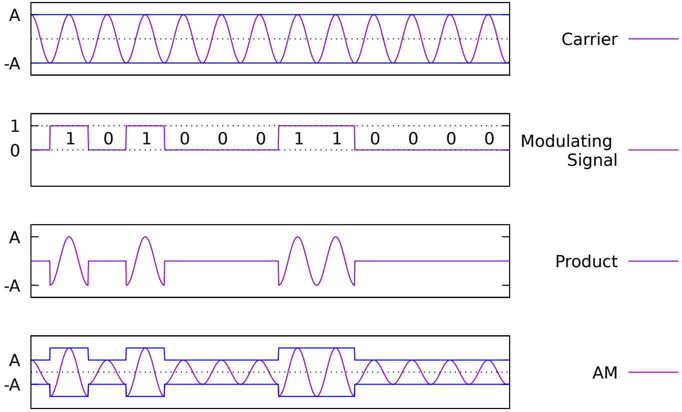
Amplitude Modulation (AM)

- The most intuitive way of modulating a signal is changing its amplitude.
- The carrier is $c(t) = Acos(2\pi f_c t)$. It must be known to both sender and receiver.
- We want to encode another signal $m(t)$ in the carrier.
- The modulated signal $am(t)$ is given by:

$$am(t) = c(t)m(t) + c(t)$$

Digital Modulation





AM Decoding

- The receiver receives $am(t) = c(t)m(t) + c(t)$
- The receiver also knows the carrier signal $c(t)$, so it inverts the signal:

$$m(t) = \frac{am(t) - c(t)}{c(t)}$$

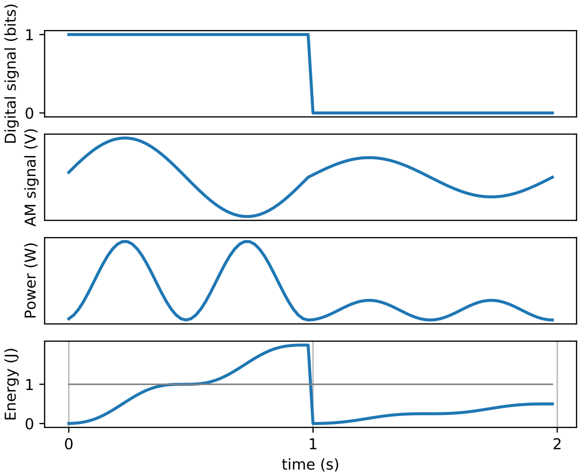
Limits of Nyquist Theorem

- The theorem assumes a communication with no noise.
- In a perfect communication, you can always increase the number of levels, and this will give you a higher bit-rate.
- But when there is noise, the estimation of amplitude and phase are not perfect.
- They will be somewhere close to the point you expect.
- If the noise is too high, you can decode the symbol incorrectly.

More bits Requires a Better Receiver

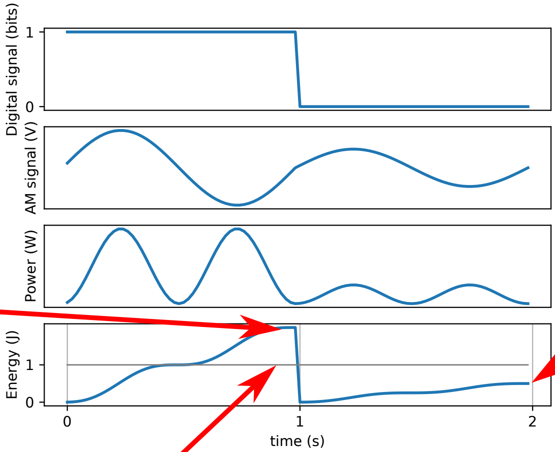
- How do you decode a digital signal?
- You have to measure the energy that a symbol carries and decide to what code it corresponds to.
- To measure the power you need to compute the squared value of the signal, and compute the integral on the length of the symbol.
- Let's consider a carrier at 1Hz, one symbol per second

AM demodulation: 1-bit decoding



Decoding Levels

- In the last diagram, at the end of each symbol the curve gives you the amount of energy you received
- If it is higher than the threshold, the data is decoded to 1, or else, to 0

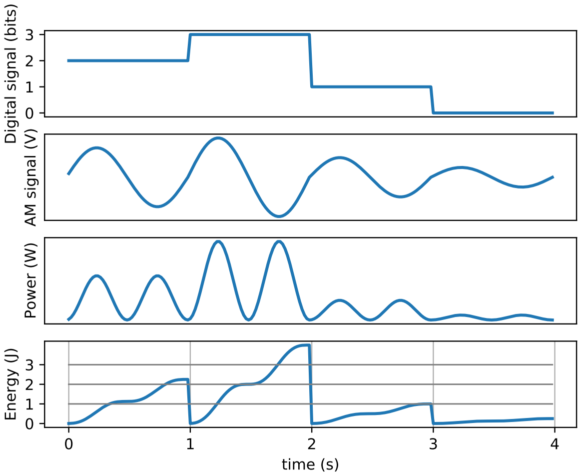


Energy is higher than the threshold: the bit is decoded as 1

Energy is lower than the threshold: the bit is decoded as 0

Threshold value differentiating 0 and 1

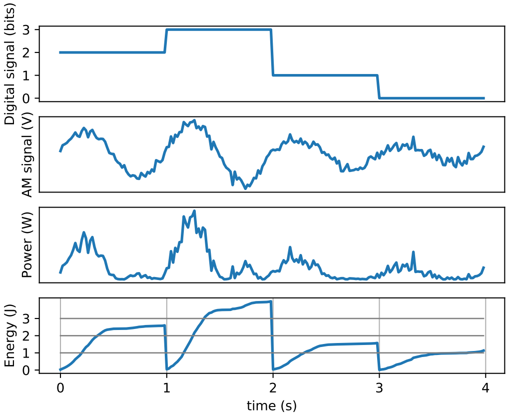
AM demodulation: 2-bit decoding



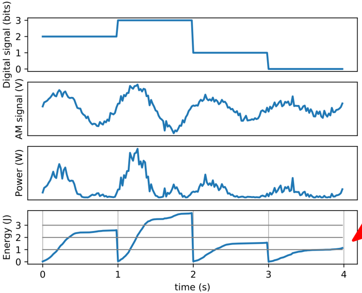
Need a Better Receiver

- Now there are more than one single threshold
- The difference between one level and the other is smaller
- If you add some noise, the detection is more likely to be wrong than in the previous case.

AM demodulation: 2-bit decoding with Noise



AM demodulation: 2-bit decoding with Noise



The last bit turned into '1'