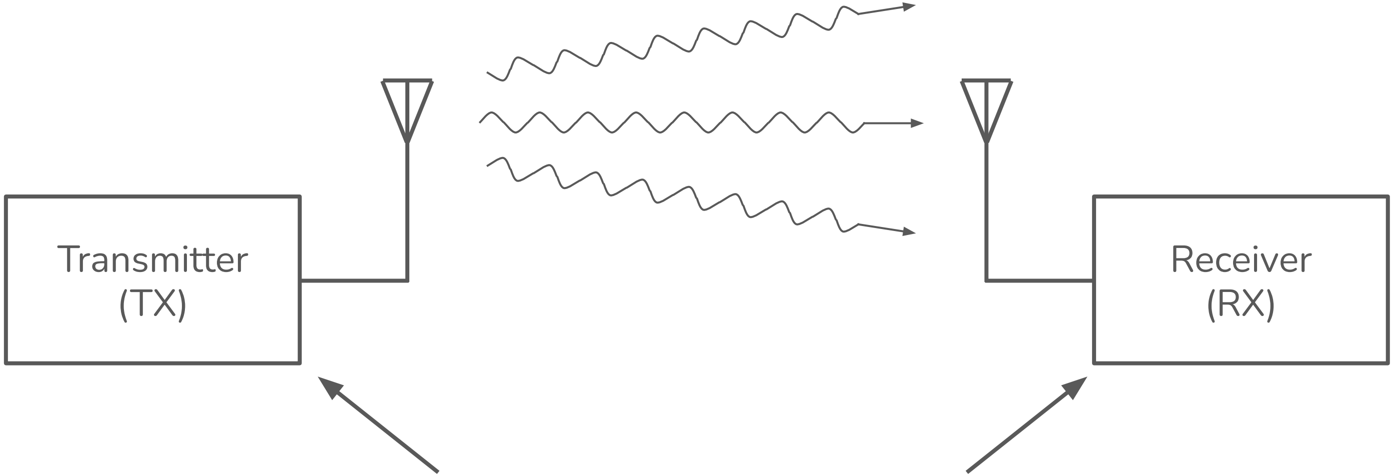
Key Concepts in Wireless Communication

Shadi Youssef

Radio Link

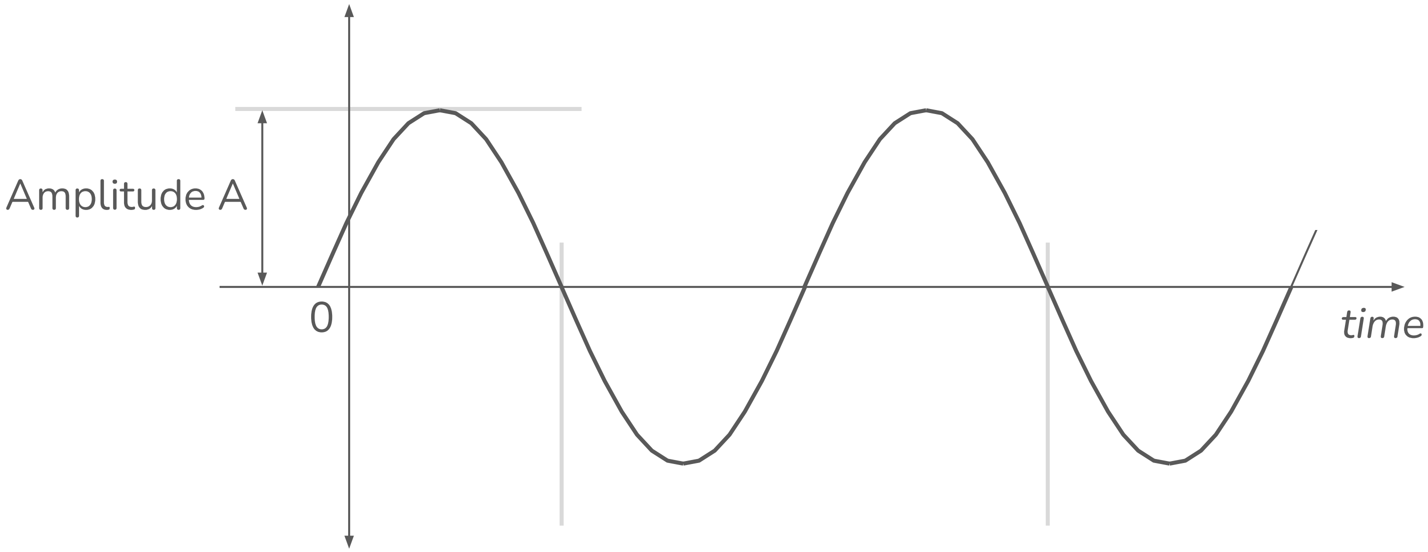


Basic concepts that make these two blocks work

Signal Power

Average Power of Sine Wave

Average power = $A^2/2$



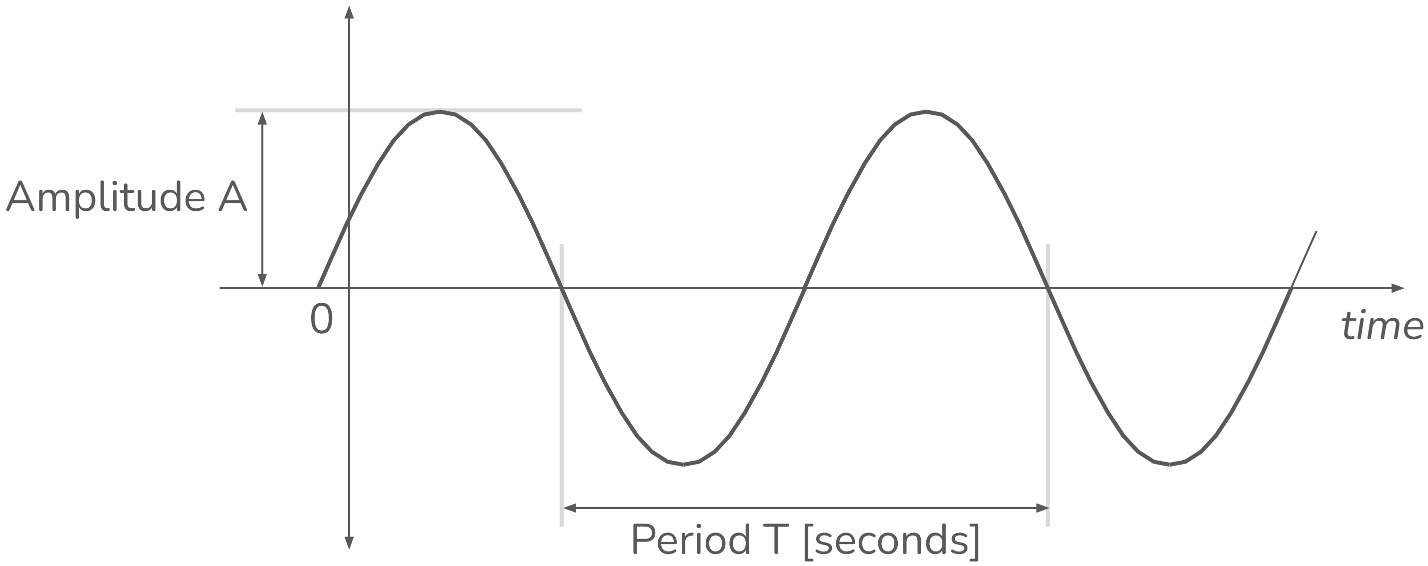
Typical Radio Sensitivity Levels

- Radio sensitivity = minimum signal power that can be detected by the receiver

Radio System	Sensitivity [W]	
WiFi	10^{-8}	
Bluetooth	10^{-10}	microvolts range
5G	10^{-11}	
GPS	10^{-17}	nano-volts range
Imaging radar (per pixel)	10^{-21}	sub-nano-volts range

Signal Spectrum

Sine Wave – Time Domain

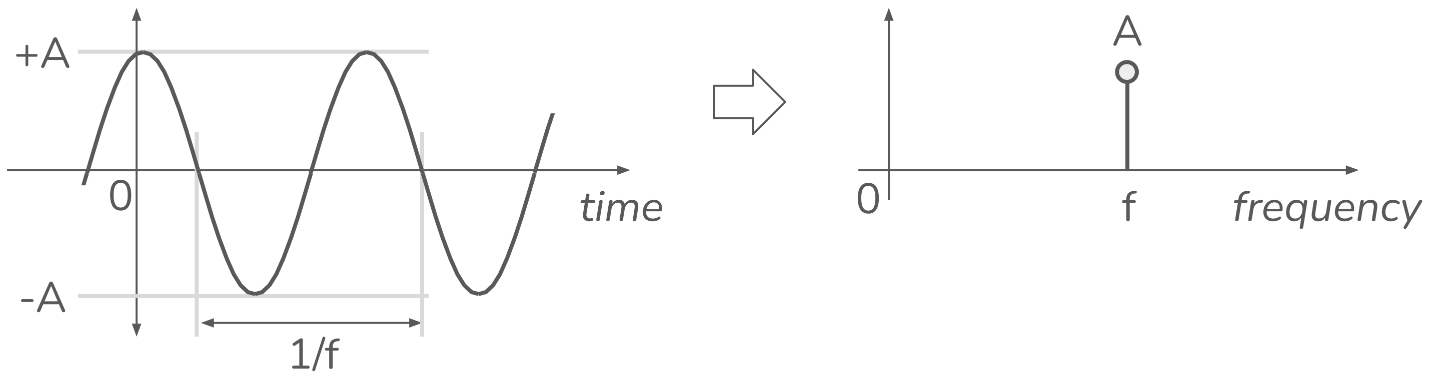


Frequency f = 1 / T [Hertz]

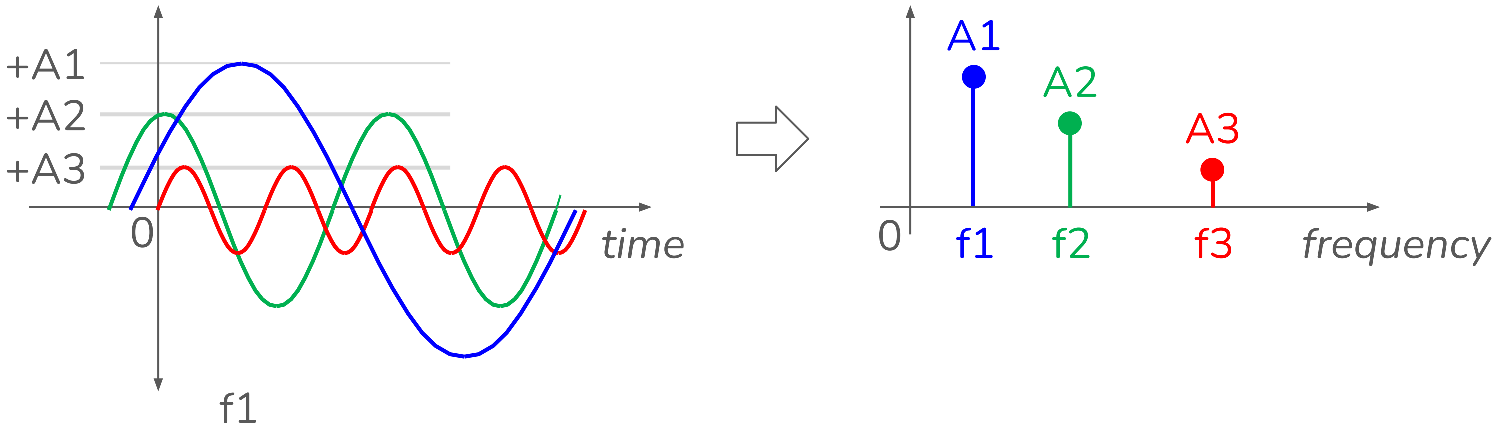
In the US, AC power is delivered at 60 Hz (60 cycles per second)

An X-band radar system transmits and receives at 10 GHz (10 billion cycles per second!)

Sine Wave – Frequency Domain

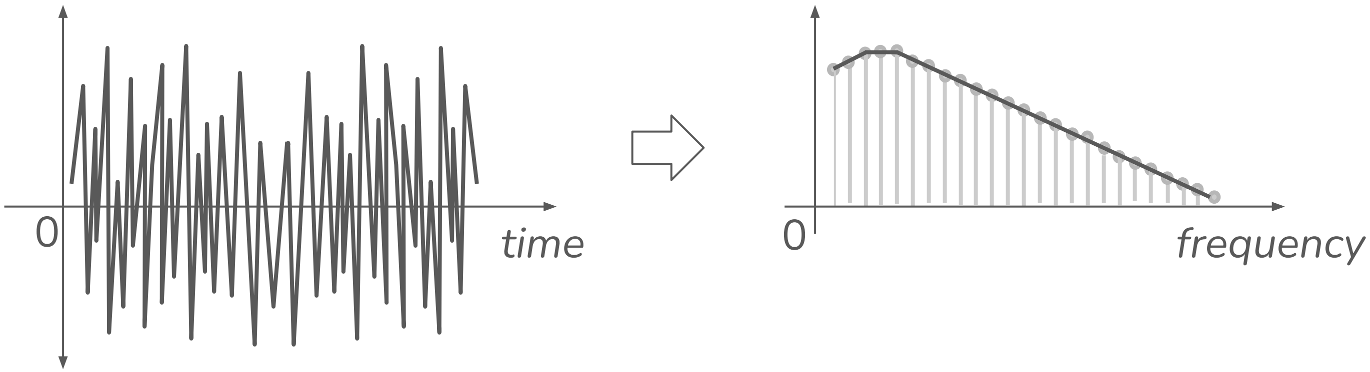


Multiple Sine Waves



Even more sine waves

- Analyzing real life signals is not easy in the time domain
- <u>Example:</u> Audio signal



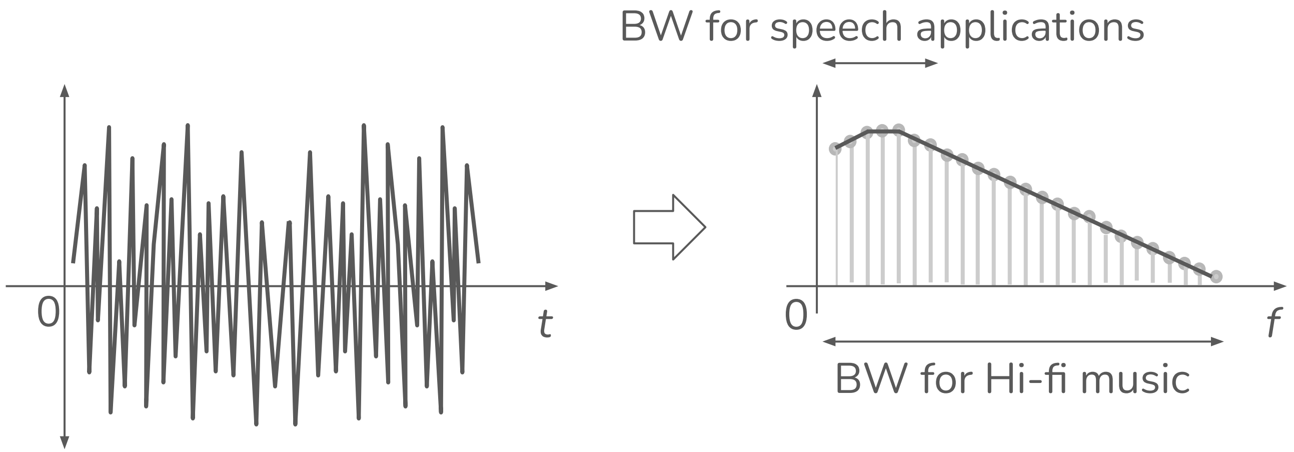
Can't see the different tones here

But can clearly see them here

Signal Bandwidth

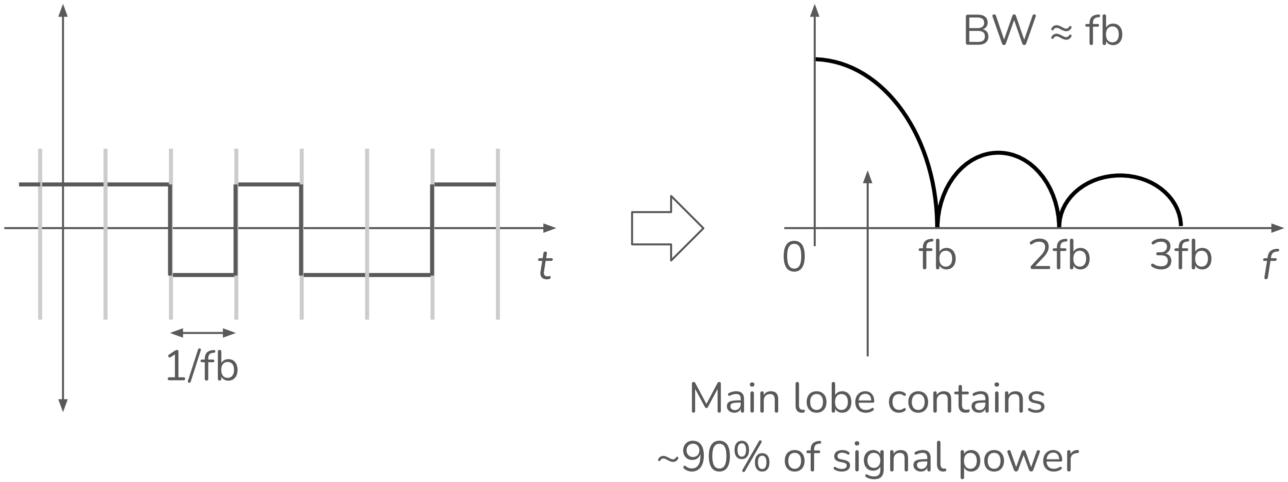
Application Determines Bandwidth

- Example: Audio signal
  - Audible range = 20 Hz – 20kHz
  - For speech → 4kHz is enough (old landline systems)
  - For high fidelity music → full 20kHz is needed



Application Determines Bandwidth

- Example: Digital Video Broadcasting (DVB-S2X)
  - Bandwidth ≈ main lobe

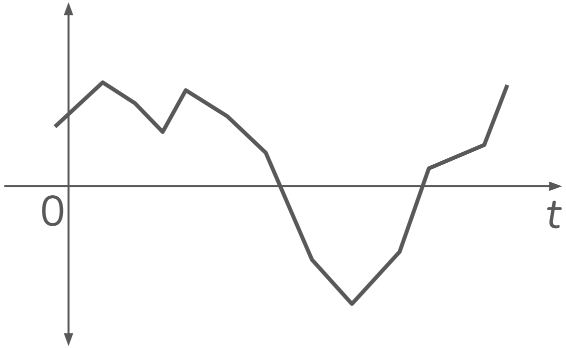


Noise

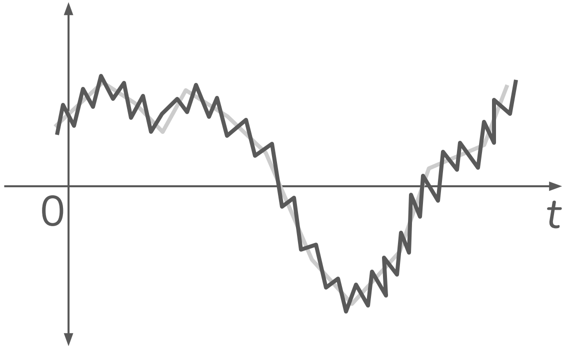
Noise is Inevitable

- All electronic devices (resistors, transistors .. etc) add noise to the signal

Ideal signal



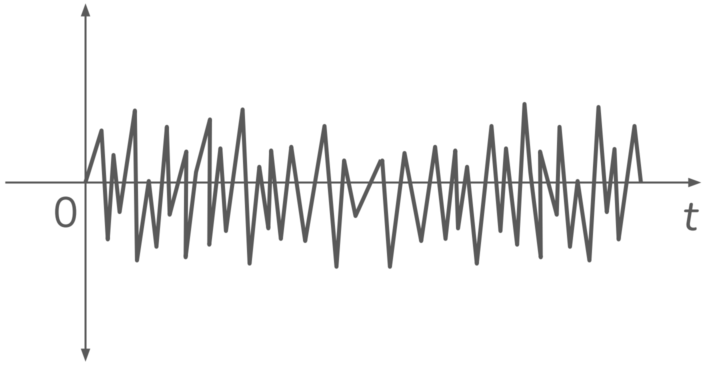
Actual signal



Thermal Noise

- Results from thermal agitation of electrons inside the device

Noise power = kB × T × BW

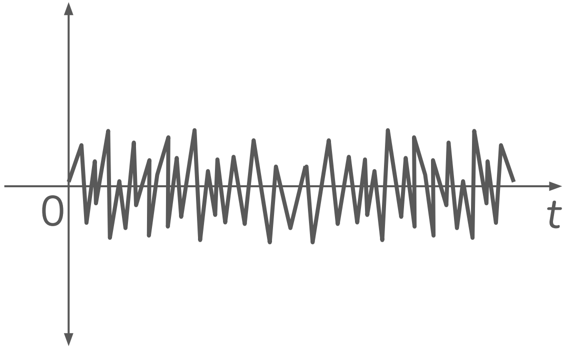


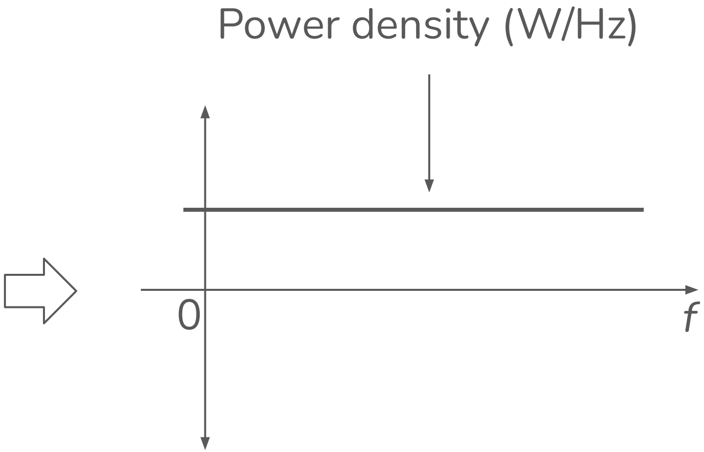
Noise power depends on temperature (makes sense)

But what about the dependence on bandwidth?

Noise Spectrum

- Thermal noise has a flat spectrum from DC to ~1THz

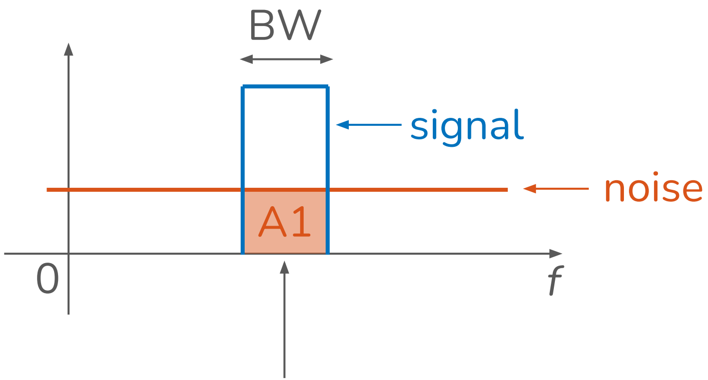




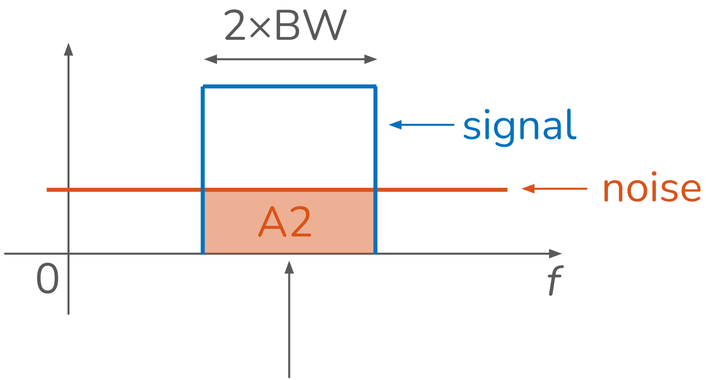
Noise power is the area under this curve

Noise Spectrum

- The wider the signal bandwidth, the more integrated noise in that bandwidth



Noise power = A1 = kB × T × BW



Noise power = A2 = kB × T × 2 BW

Higher data rates → higher bandwidth → more noise

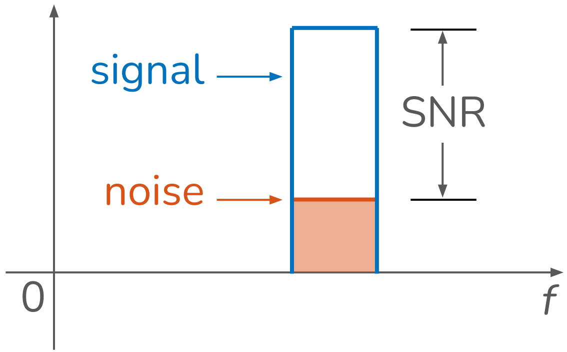
This is one reason high-speed communication is challenging

Signal-to-Noise Ratio (SNR)

- SNR = ratio of signal power to noise power
- The higher the SNR, the better the quality of the radio link

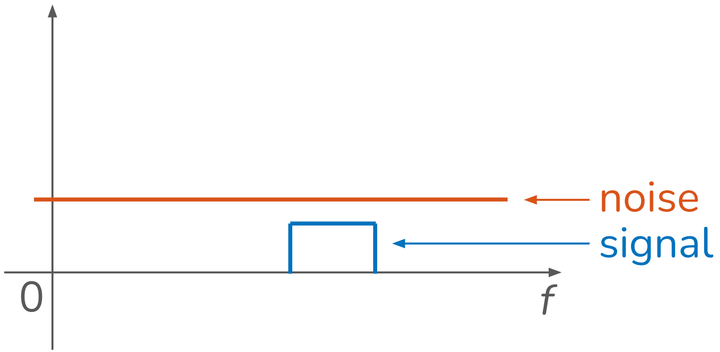
<u>Good radio link</u>

Signal above noise floor (SNR > 1)



<u>Bad radio link</u>

Signal buried in noise (SNR < 1)



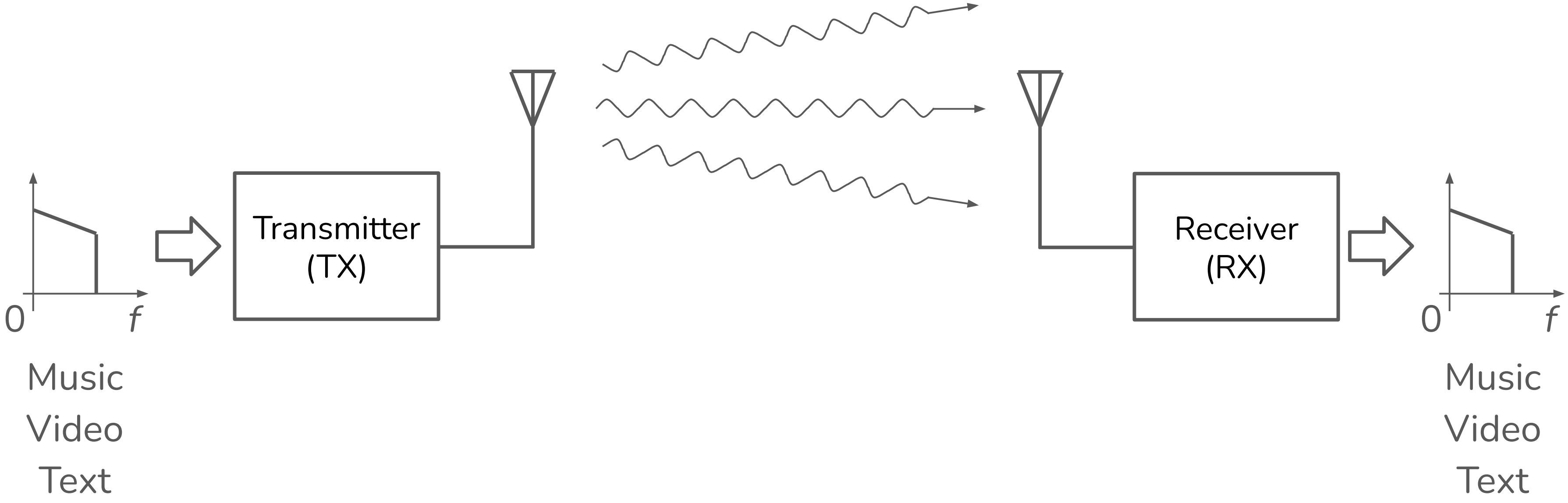
- <u>Example:</u> WiFi high speed link requires SNR > 30dB (signal > 1000x higher than noise)

Low Temperature = Low Noise = Better SNR

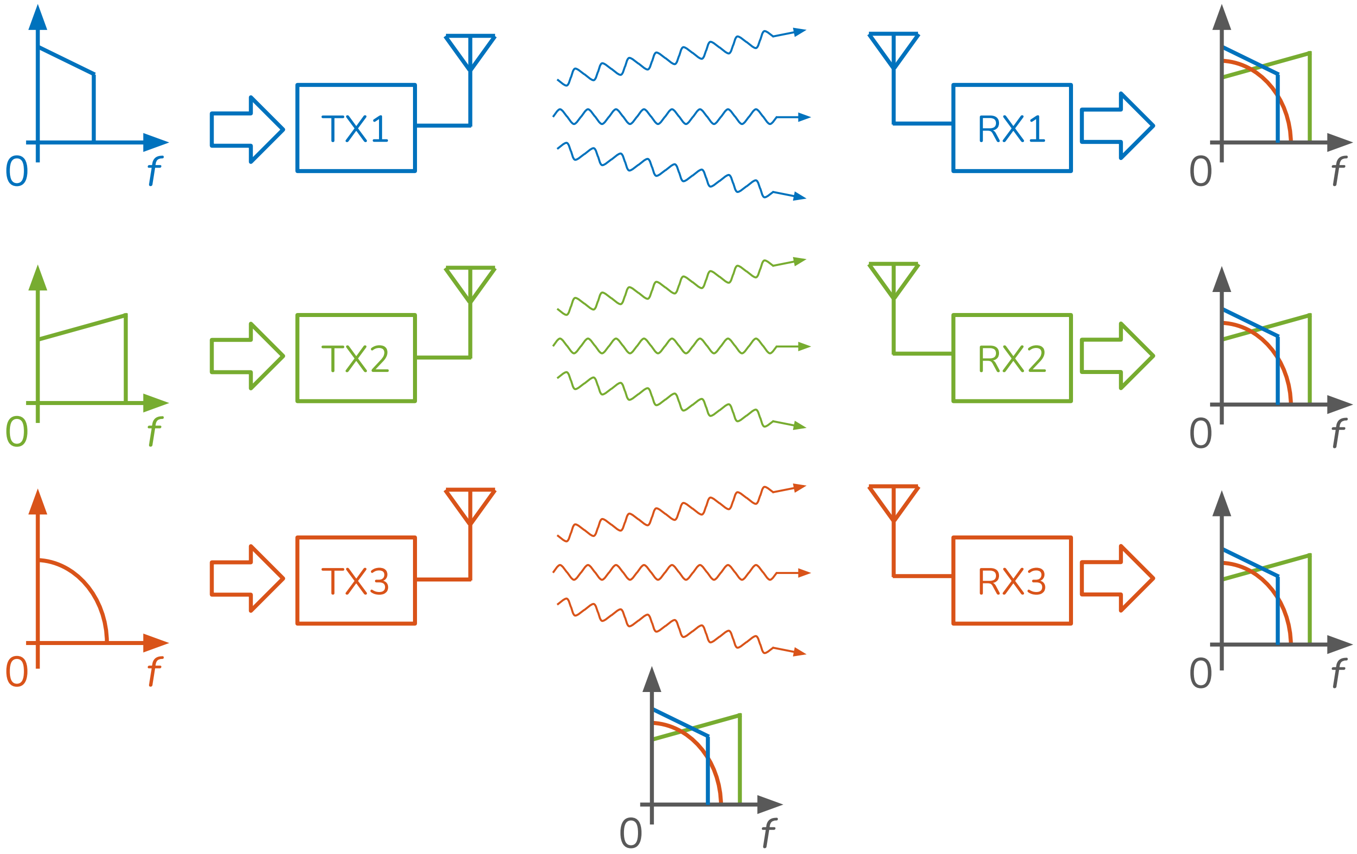
- <u>Example:</u> The Very Large Array (VLA) radio astronomy telescope in New Mexico
  - Receiver cryogenically cooled down to 40K
  - Low temperature reduces noise and allows sensing very faint signals
  - X-band sensitivity is ~2 femto-Watts in a 1GHz bandwidth

Modulation

Single Wireless System

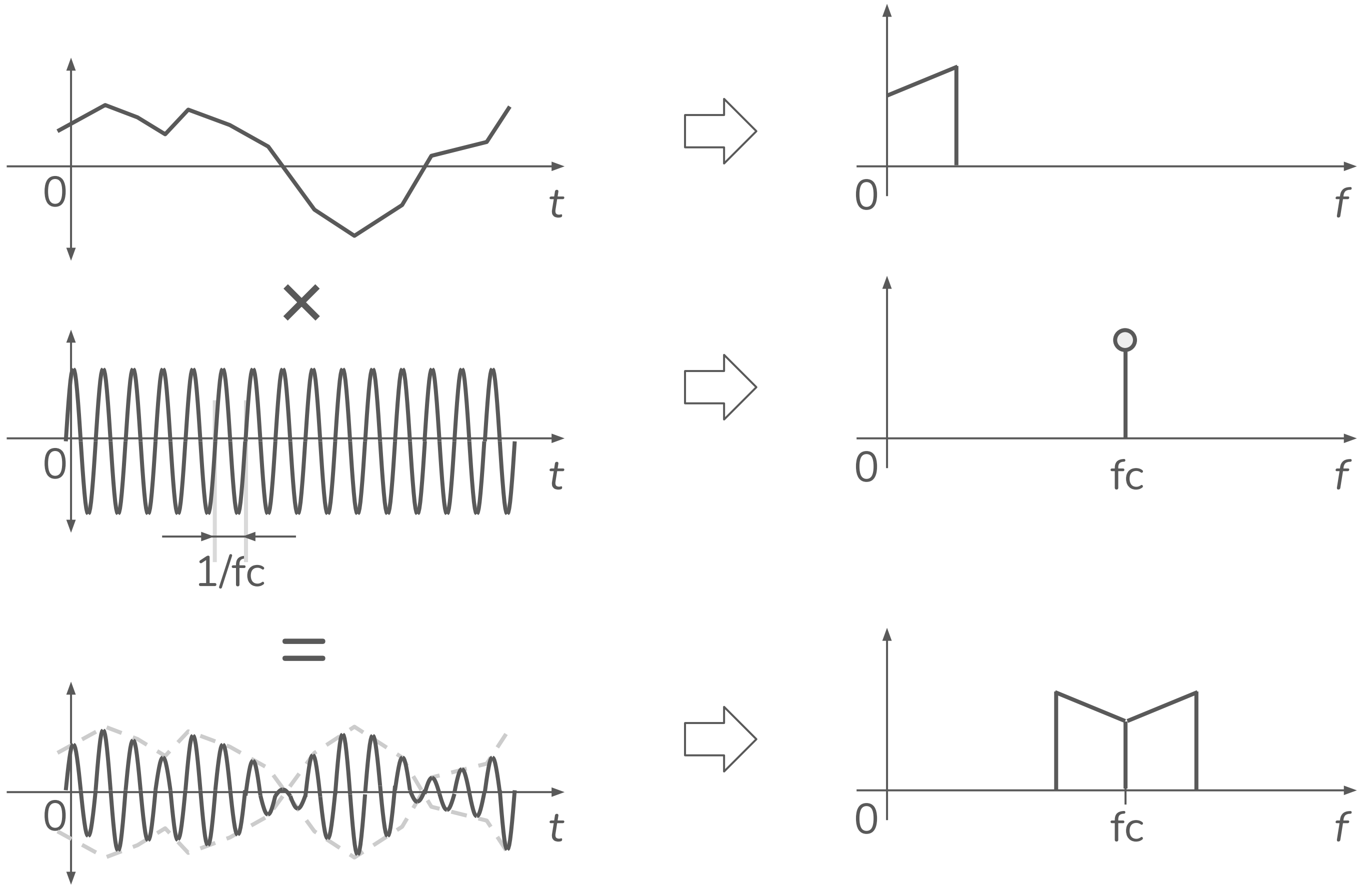


Multiple Wireless Systems

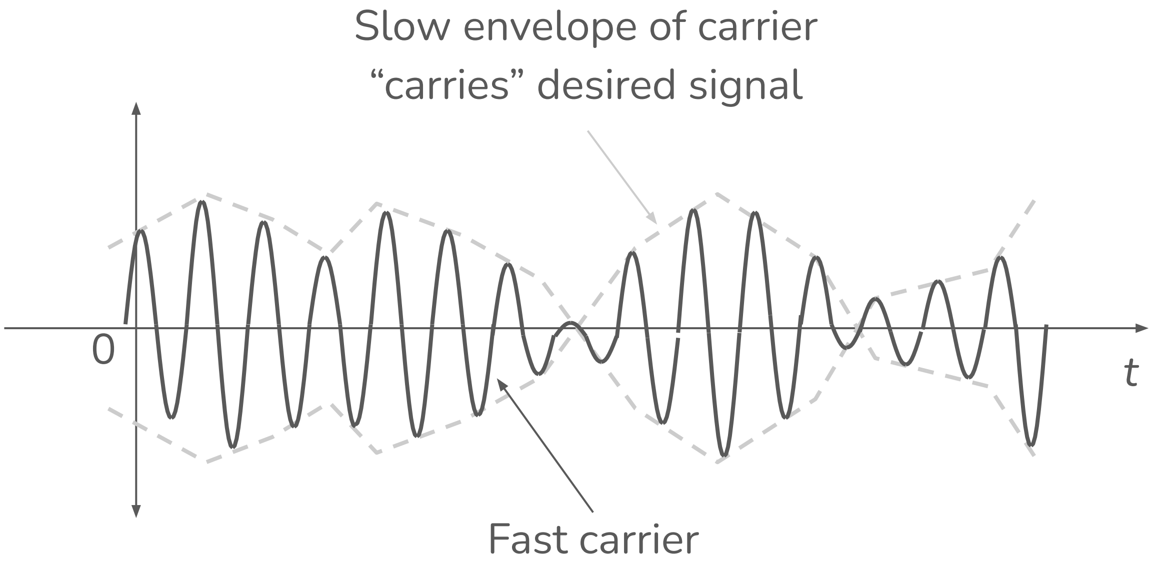


Signals interfering over-the-air

Solution: Shift the Spectrum

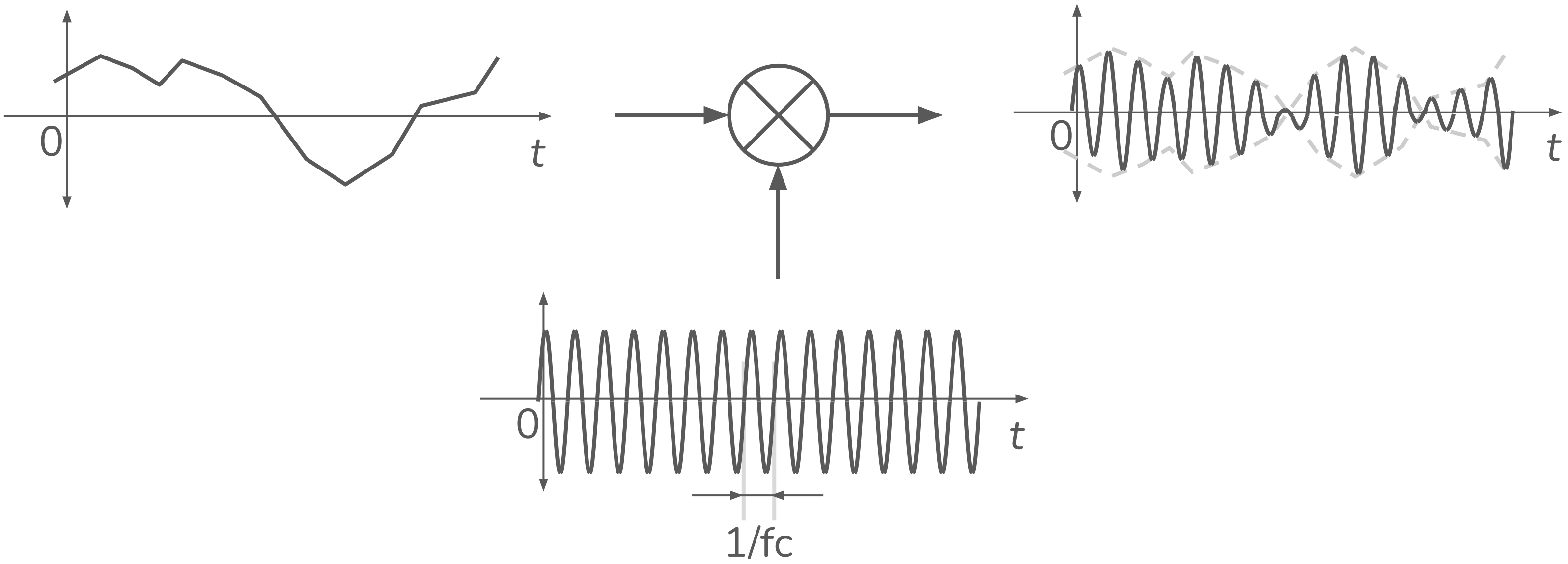


Shifting the Spectrum = Amplitude Modulation (AM)



Basic “Radio Tuner”

- A radio tuner is simply a multiplier (also called a mixer)
- Tuning = setting the carrier frequency to the desired channel



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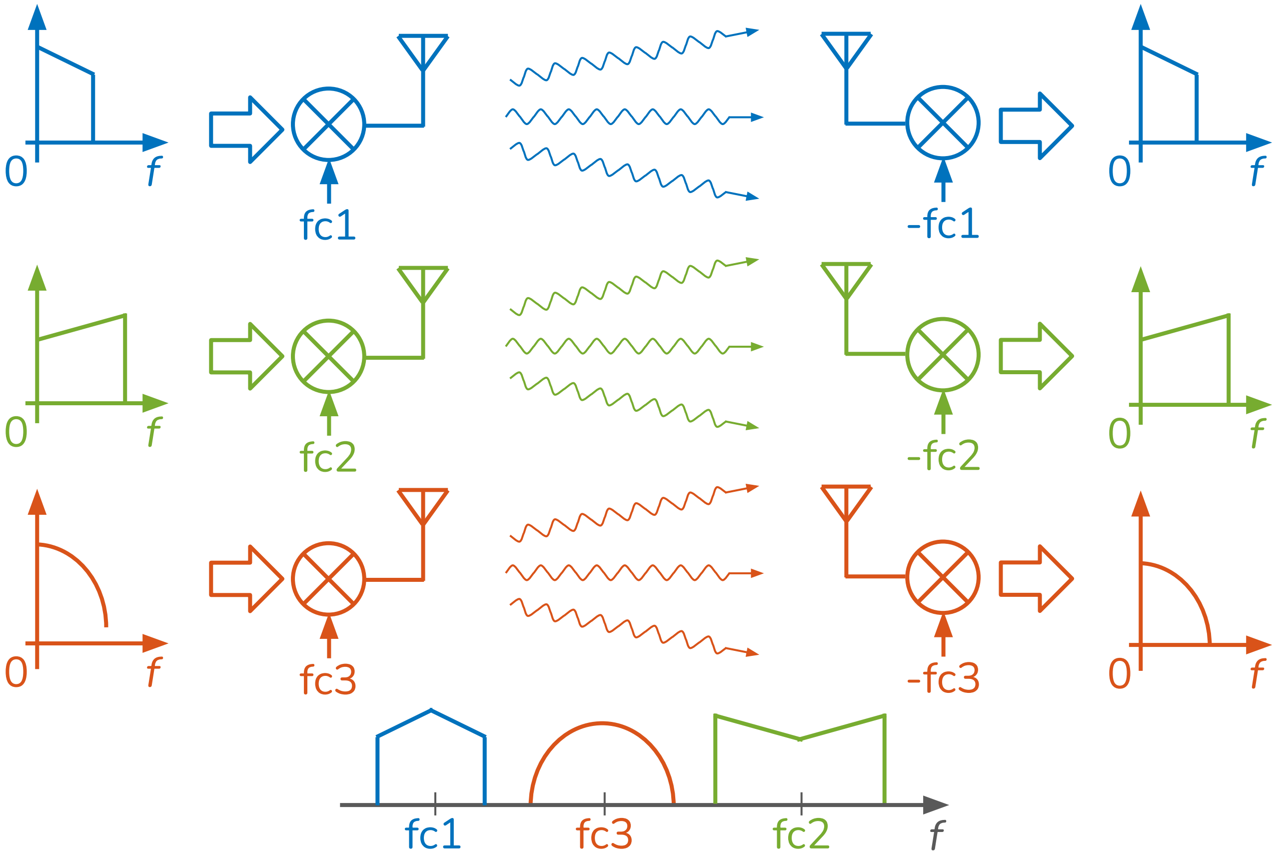
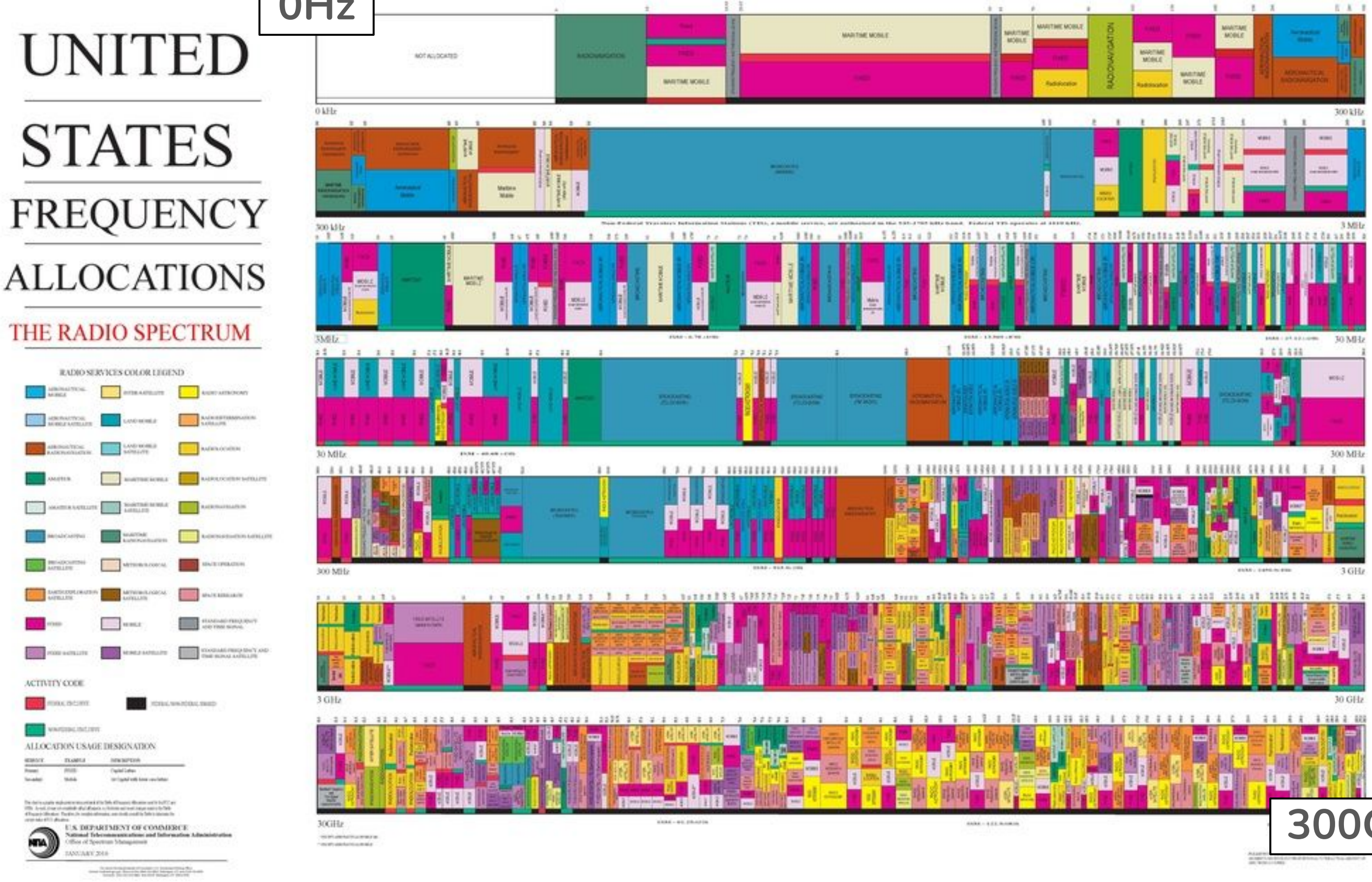


Signals are separate over-the-air

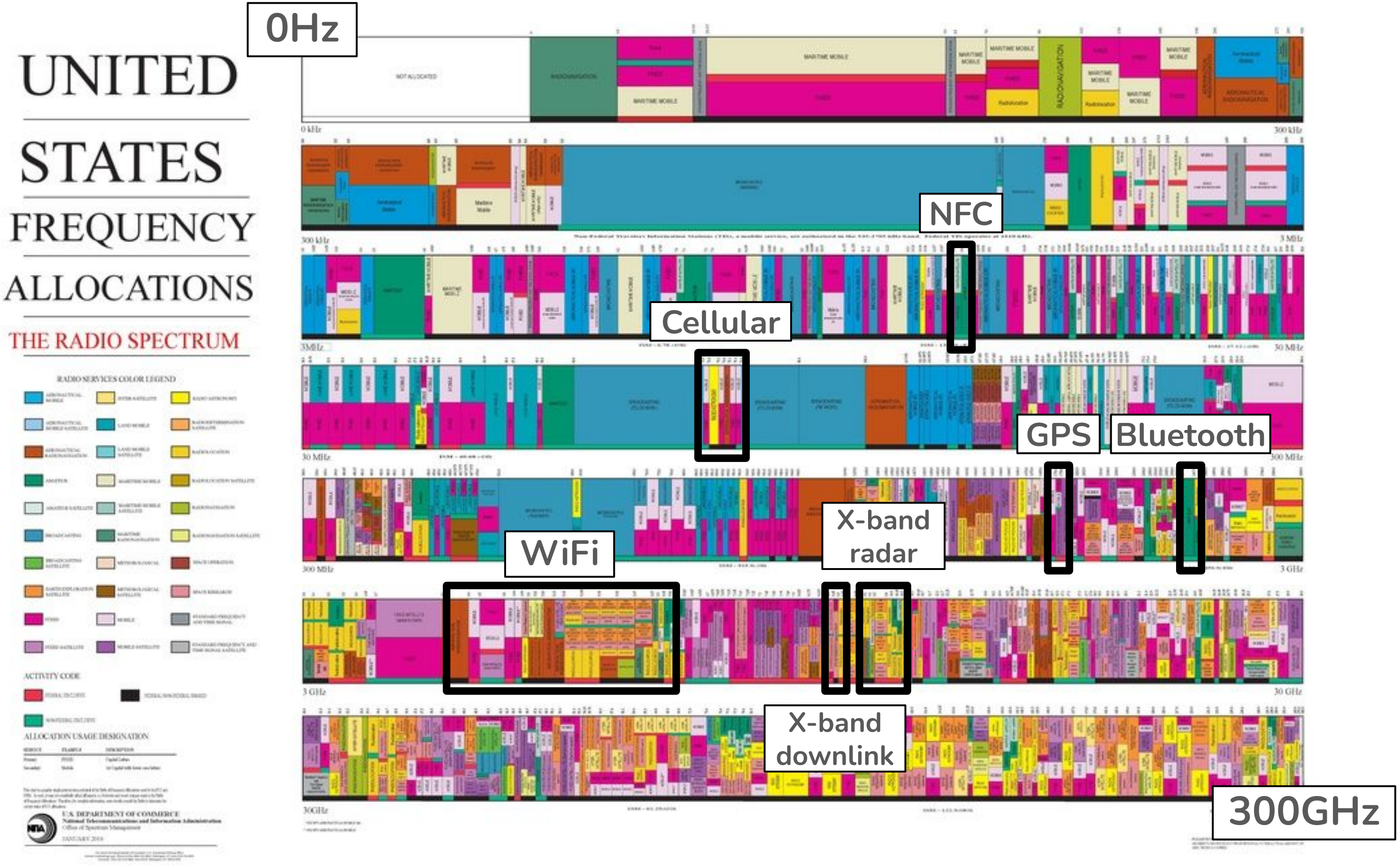
Spectrum Allocation in the US

0Hz



300GHz

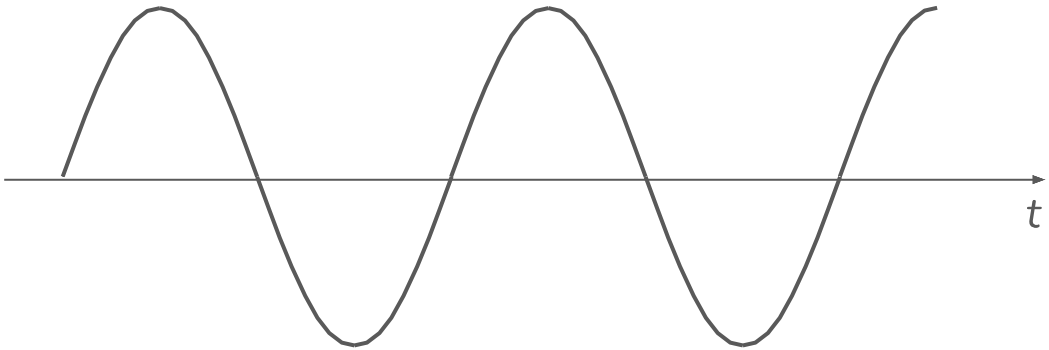
Spectrum Allocation in the US



Digital Representation of Signals

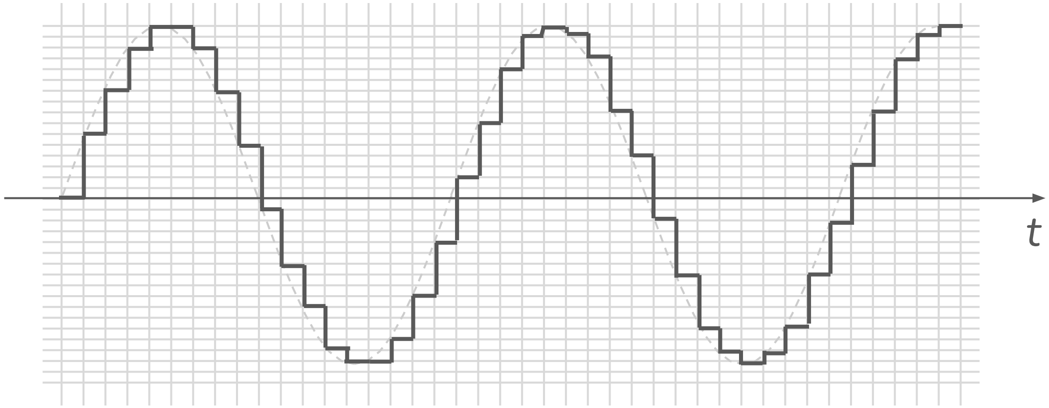
Sine Wave – Analog Representation

- Continuous time and continuous amplitude
- Infinite resolution in both time and amplitude



Sine Wave – Digital Representation

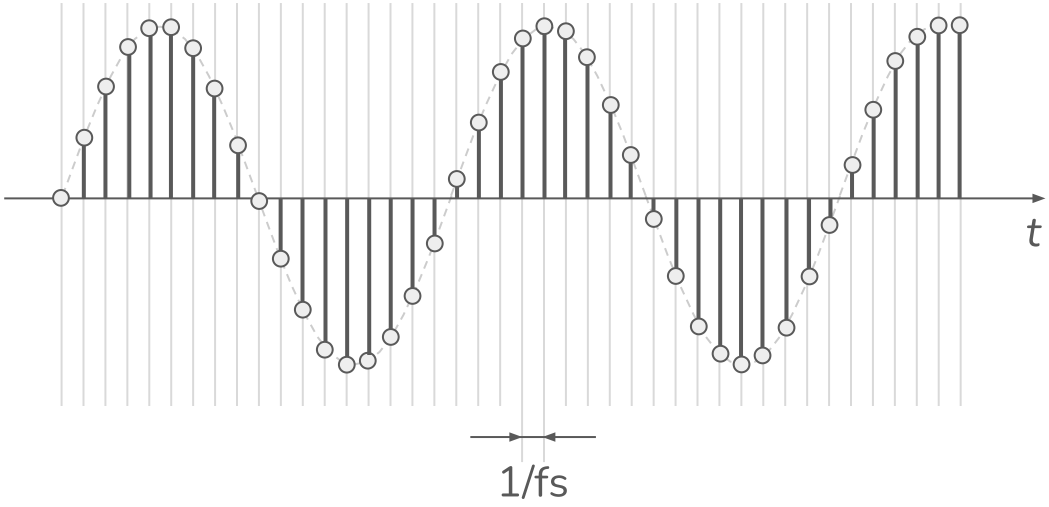
- Discrete time and discrete amplitude
- Finite resolution in both time and amplitude



Let's Start with Discrete Time

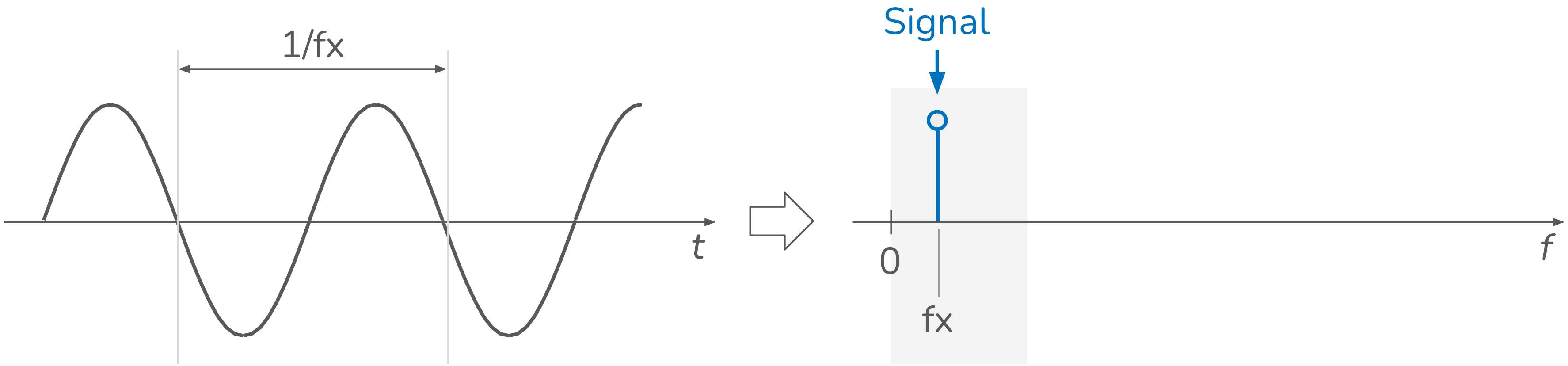
- <u>Discrete time</u> and continuous amplitude

Every clock tick, we get one value

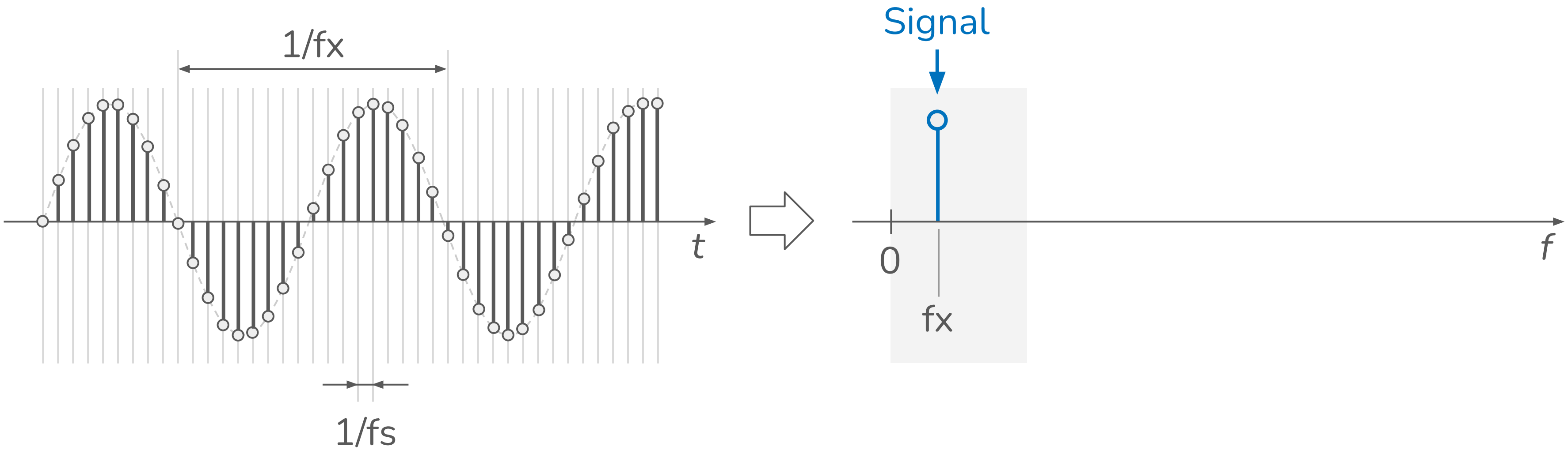


Sampling rate fs = number of samples per second

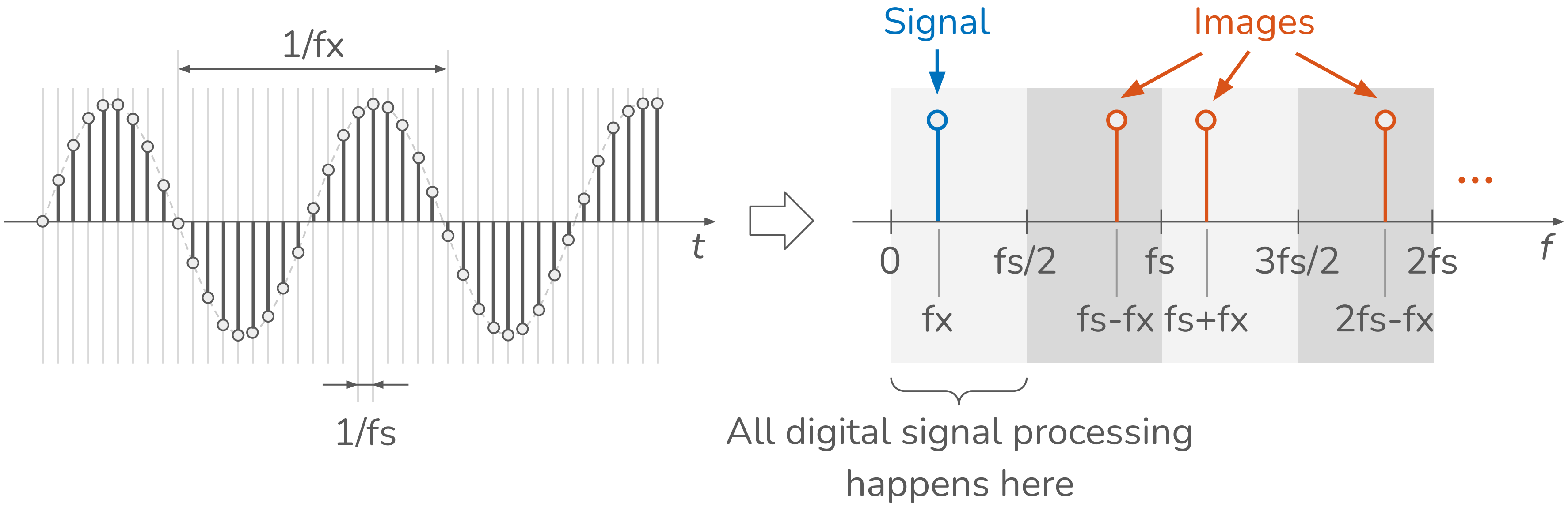
We've seen the spectrum of the analog signal before



The spectrum of a the discrete-time version is similar



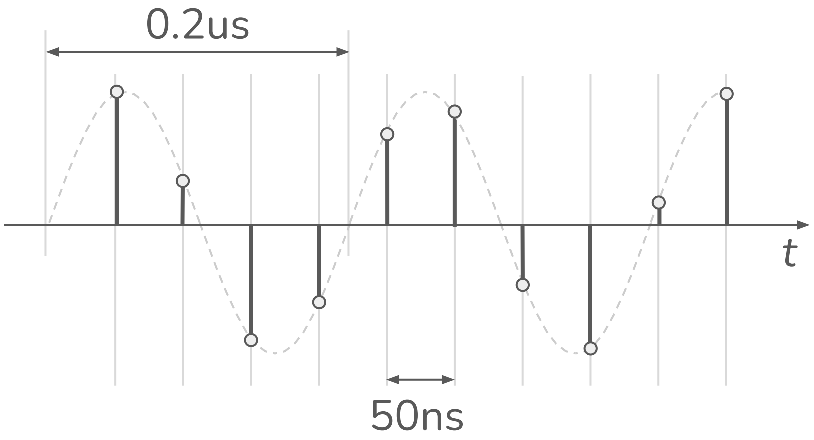
Except that it repeats every fs/2

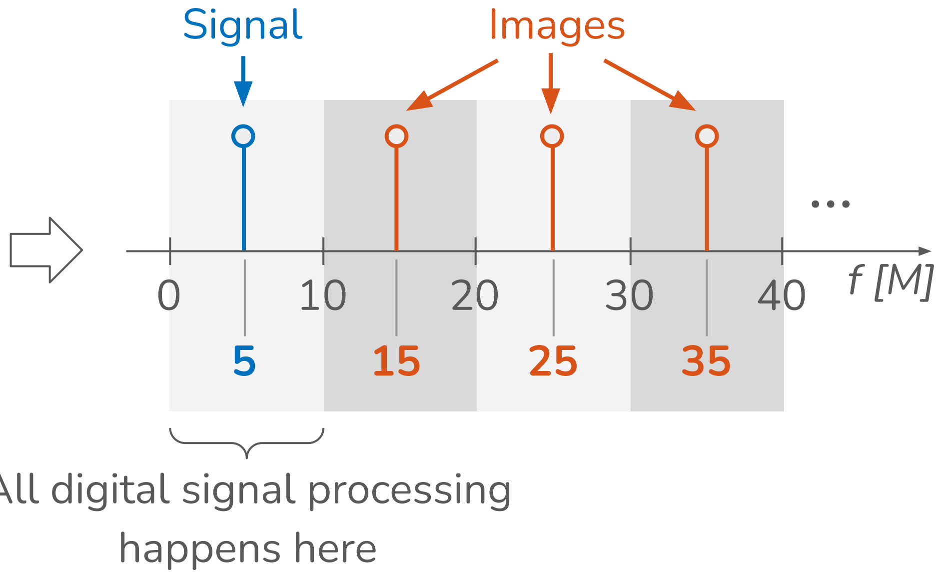


In the digital domain, the useful frequency range is 0 to fs/2

Spectrum of Discrete-Time Signal

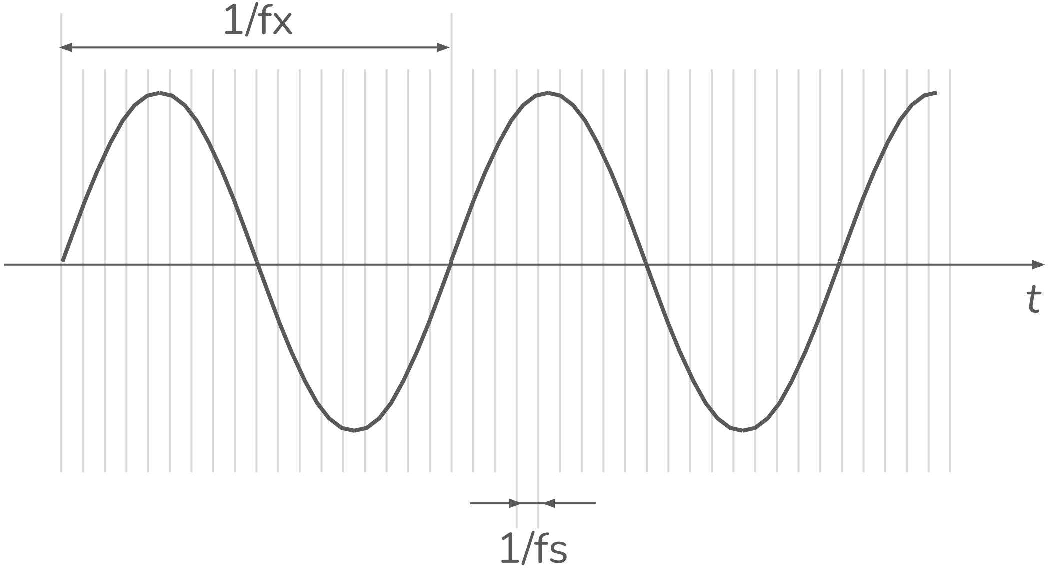
- <u>Example:</u> fx = 5MHz and fs = 20MHz





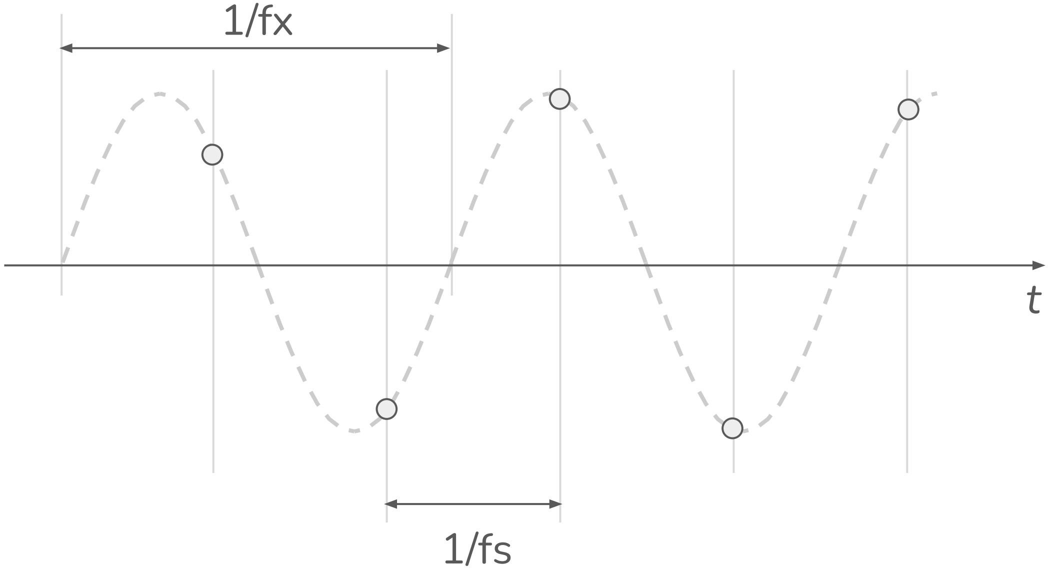
Minimum Sampling Rate of a Sine Wave

- More samples per second requires more processing power
- So what’s the minimum number of samples we can get away with?



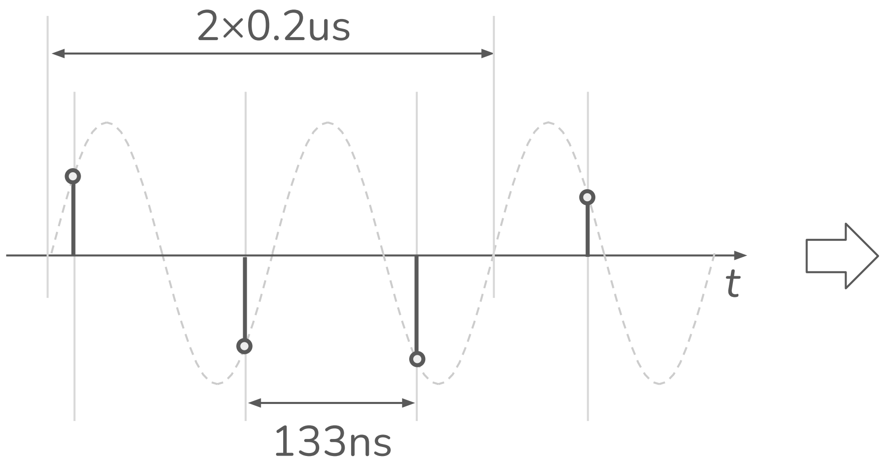
Minimum Sampling Rate of a Sine Wave

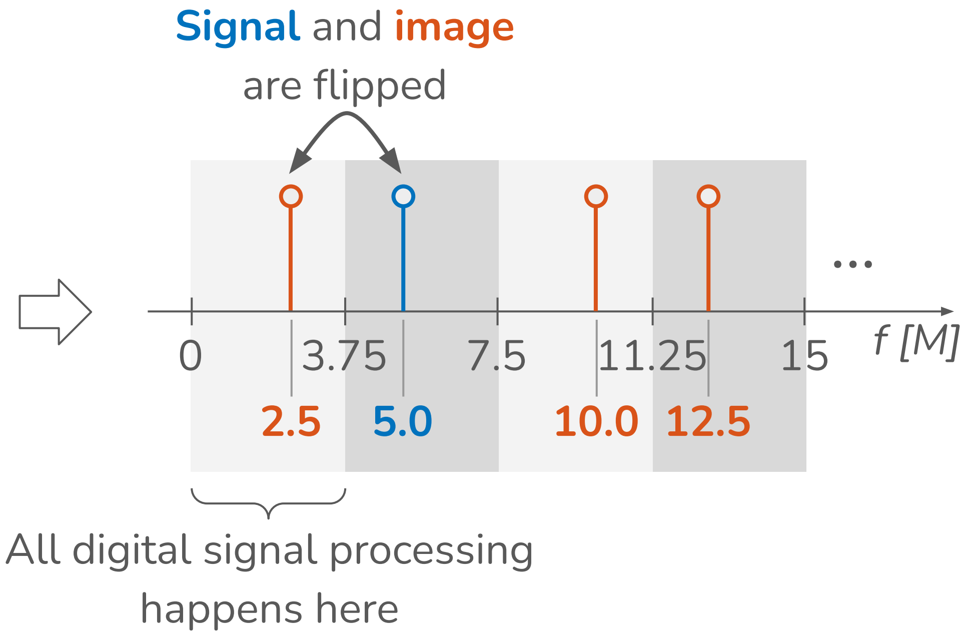
- We need <u>at least 2 samples per cycle</u>
- Why?



Minimum Sampling Rate of a Sine Wave

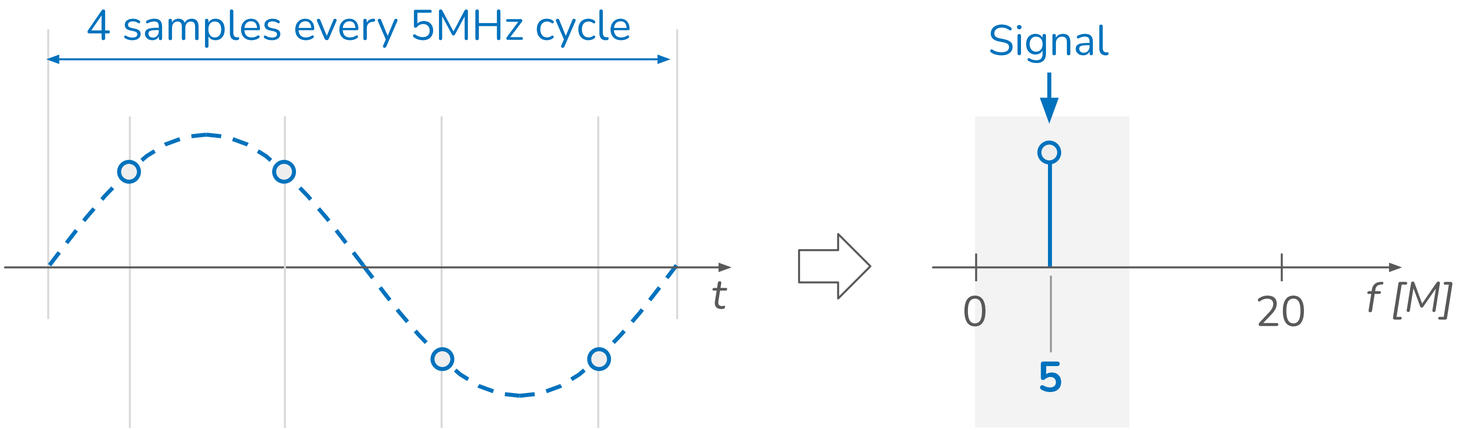
- <u>Example:</u> fx = 5MHz, fs = 7.5MHz (3 samples every 2 cycles)





Why is the discrete-time spectrum periodic?

- Representing continuous time with discrete instances introduces ambiguity
- <u>Back to the same example:</u> fx = 5MHz, fs = 20MHz



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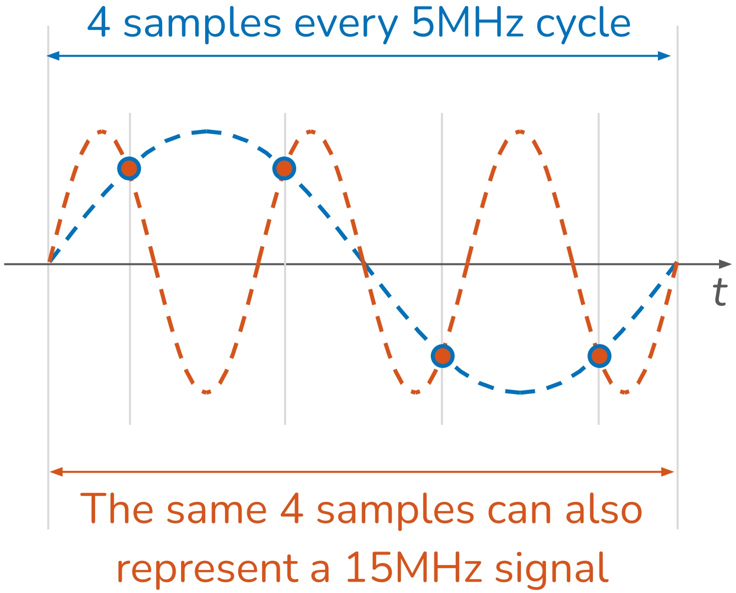
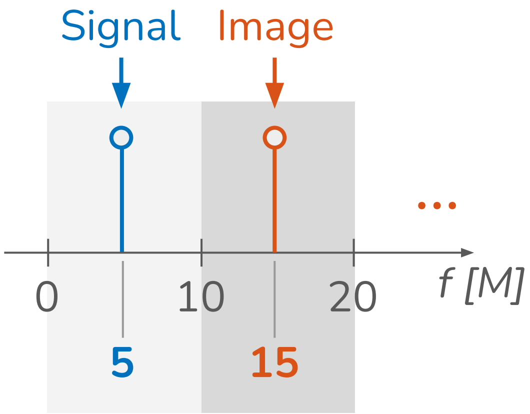
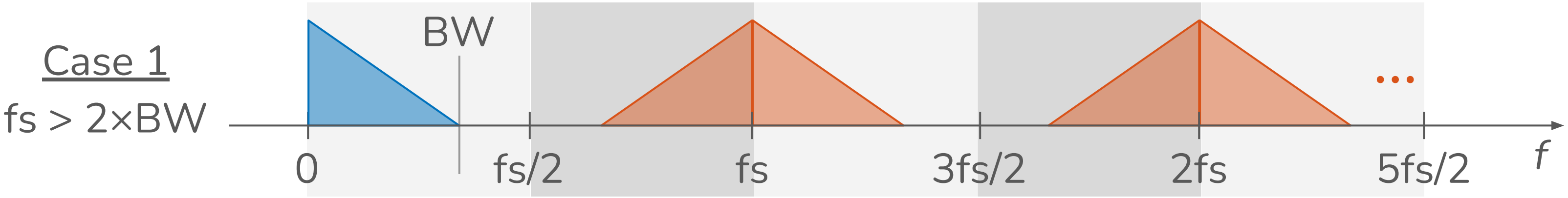




How about a more complicated signal?



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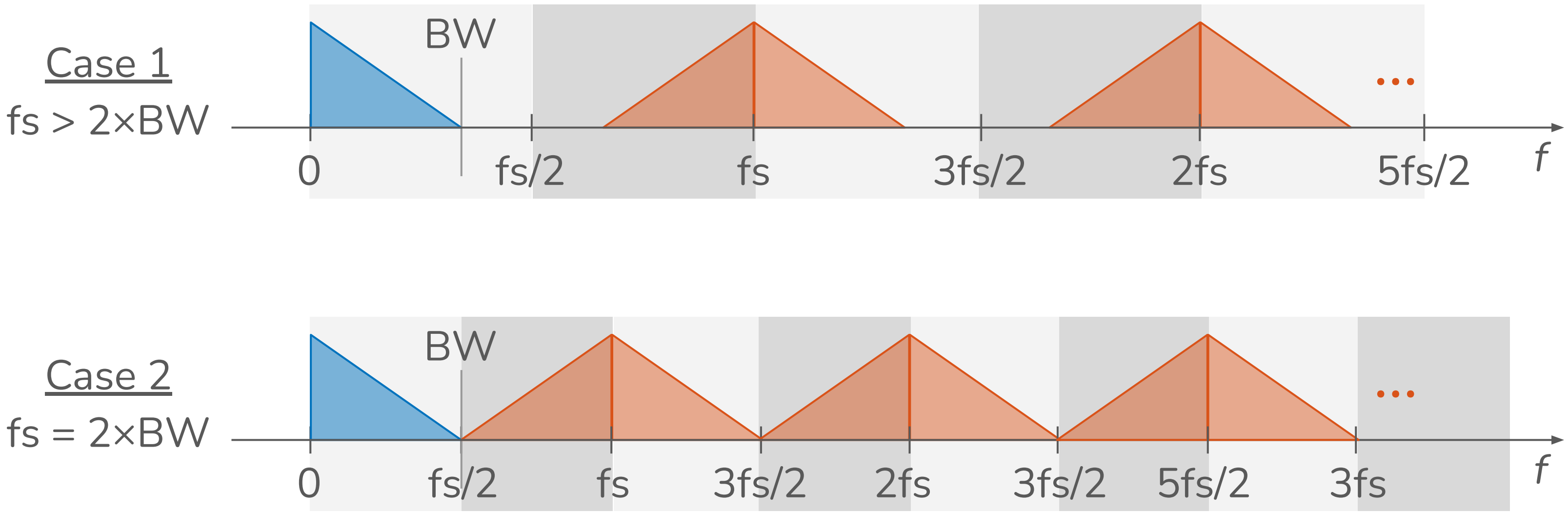

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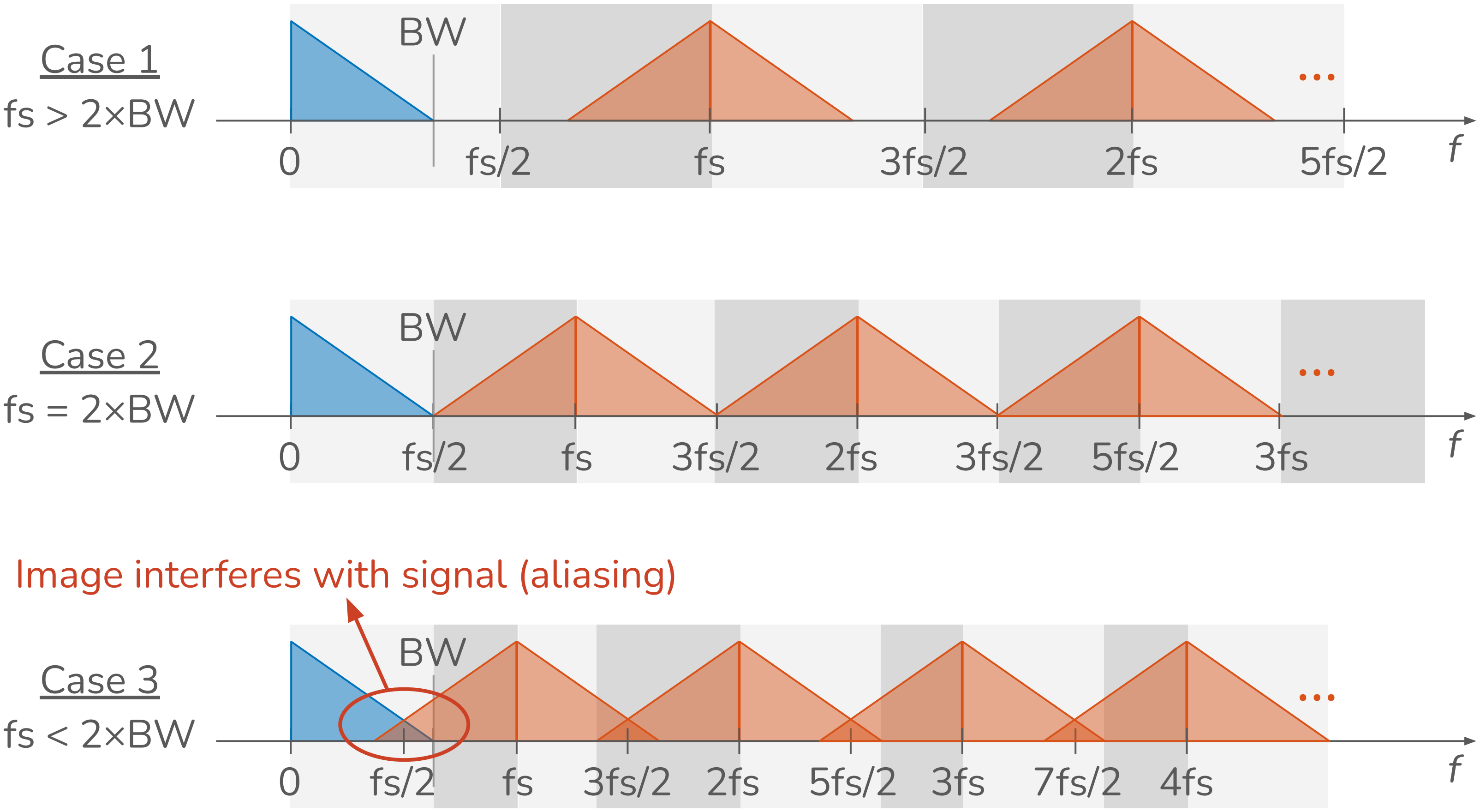
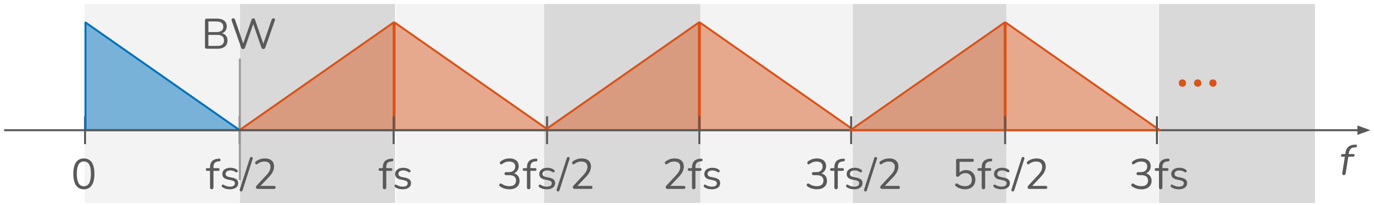


Nyquist Sampling Theorem

A signal of BW bandwidth requires a sampling rate > 2×BW



Example: Radar Signal

- Requirement: image resolution = 20cm
- Radar signal BW = c / (2 × resolution) = 750MHz
- Digital clock has to be > 2 × BW = 1.5Gsps

Example: Image Downscaling (Downsampling)

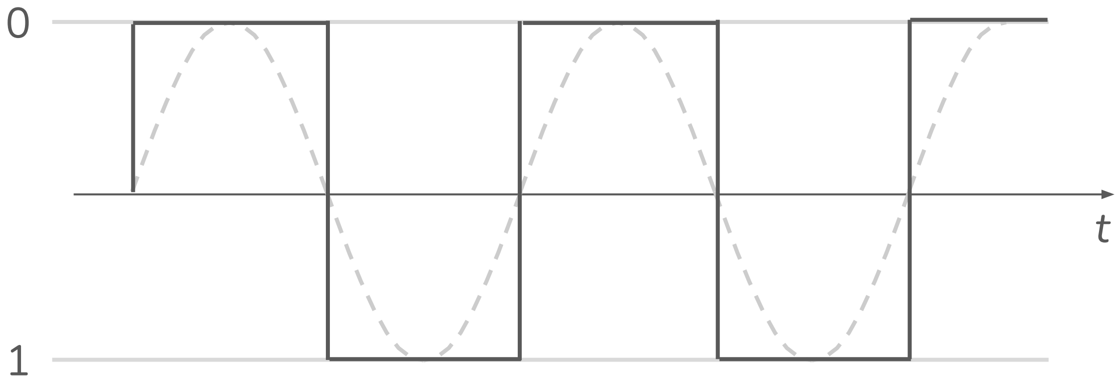
- Reducing the resolution of an image can cause aliasing

High resolution image

Low resolution image

Let’s now look at discrete amplitude

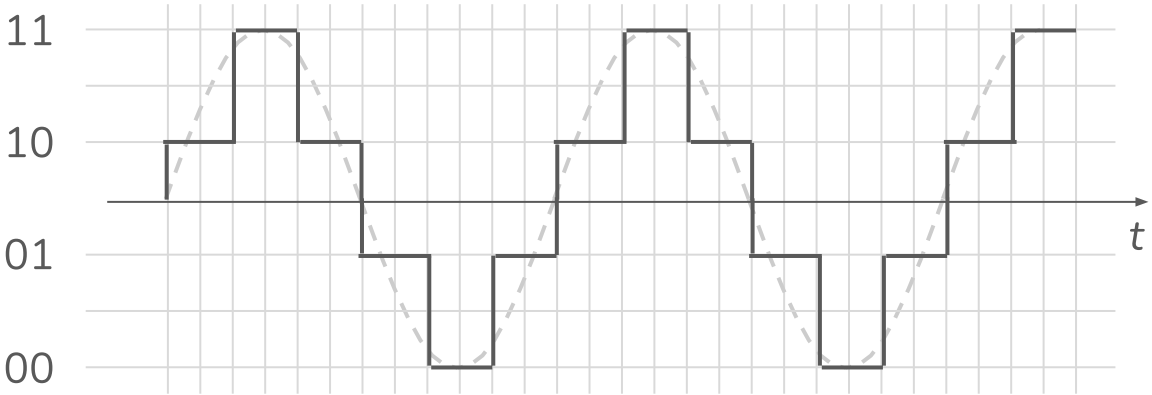
- Suppose we want to represent a sine wave with a single bit
- 1 bit → 2 levels



Looks very rough!

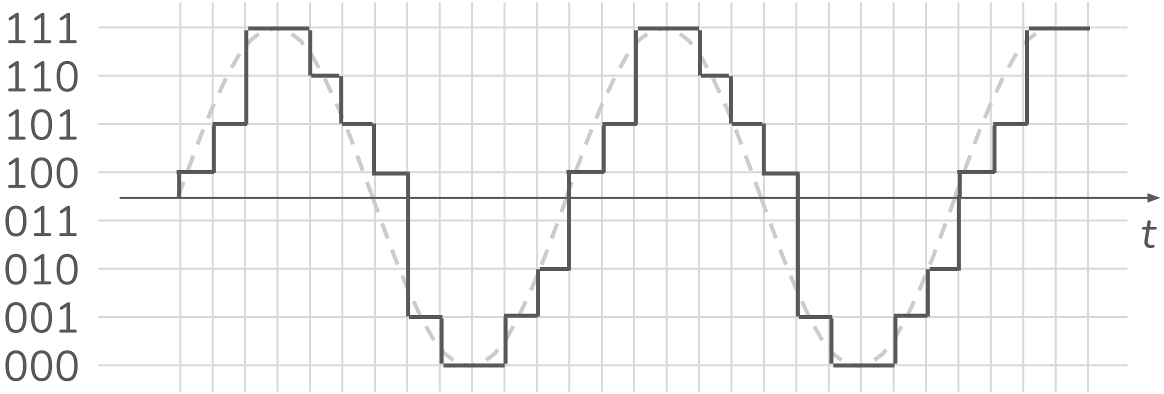
We can do better by adding one more bit

- 2 bits → 2^2 levels



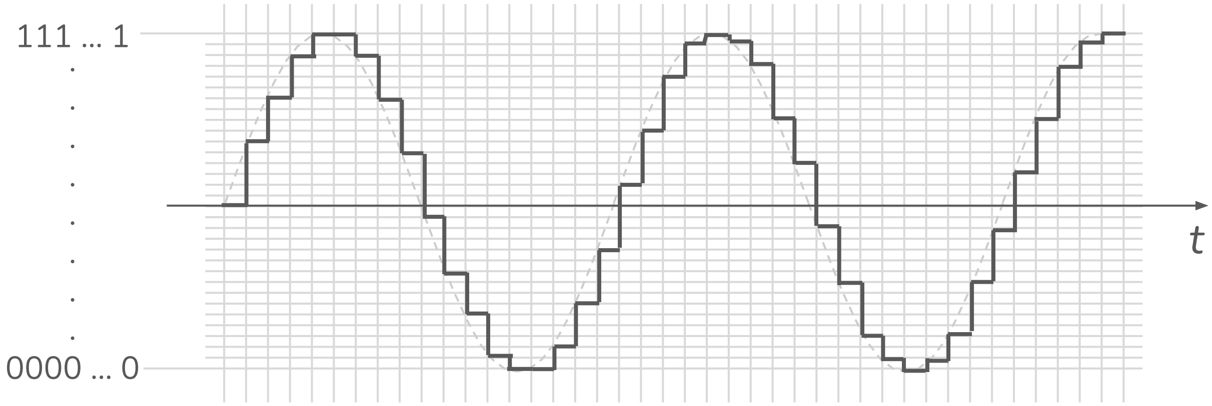
Add yet one more bit

- 3 bits → 2^3 levels



Adding more bits improves fidelity

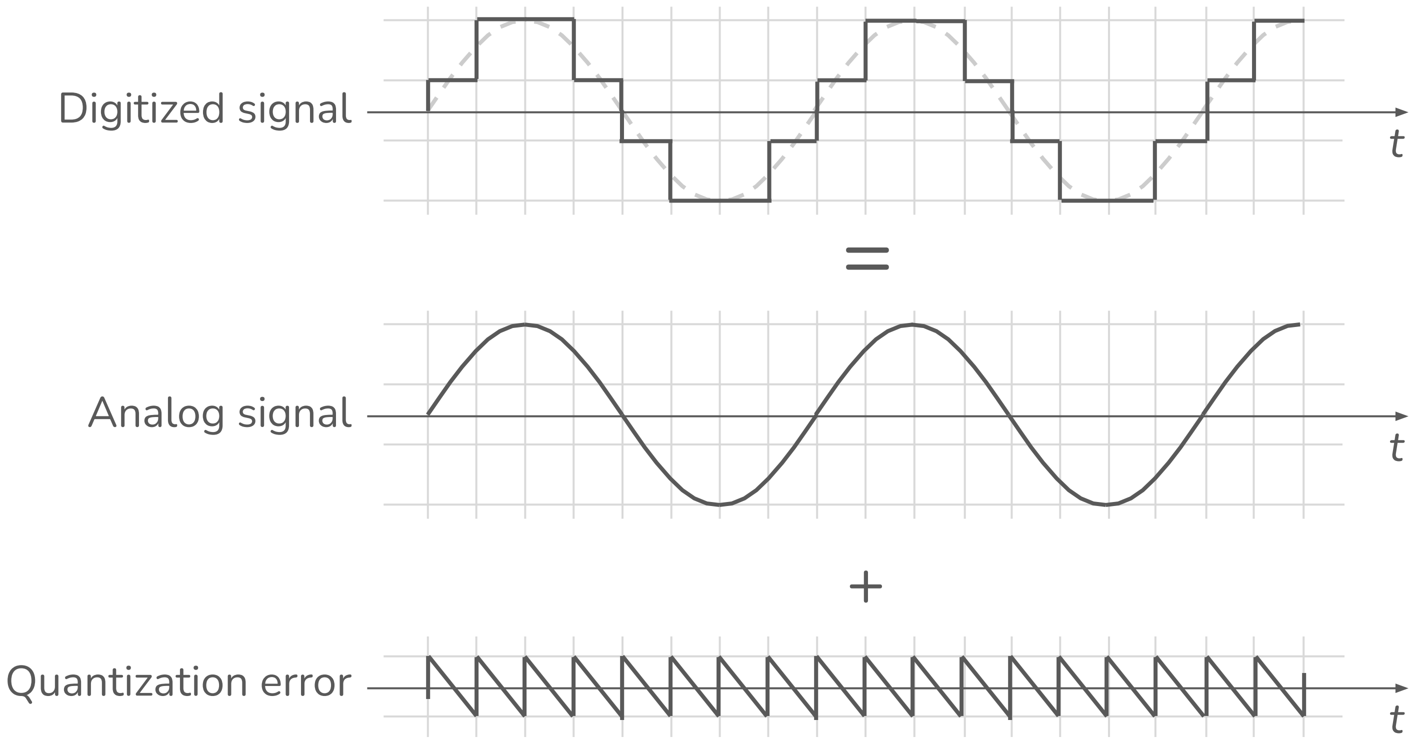
- N-bits → 2^N levels



So how many bits are enough?

Quantization Error

- Digitized signal = analog (ideal) signal + error from quantization



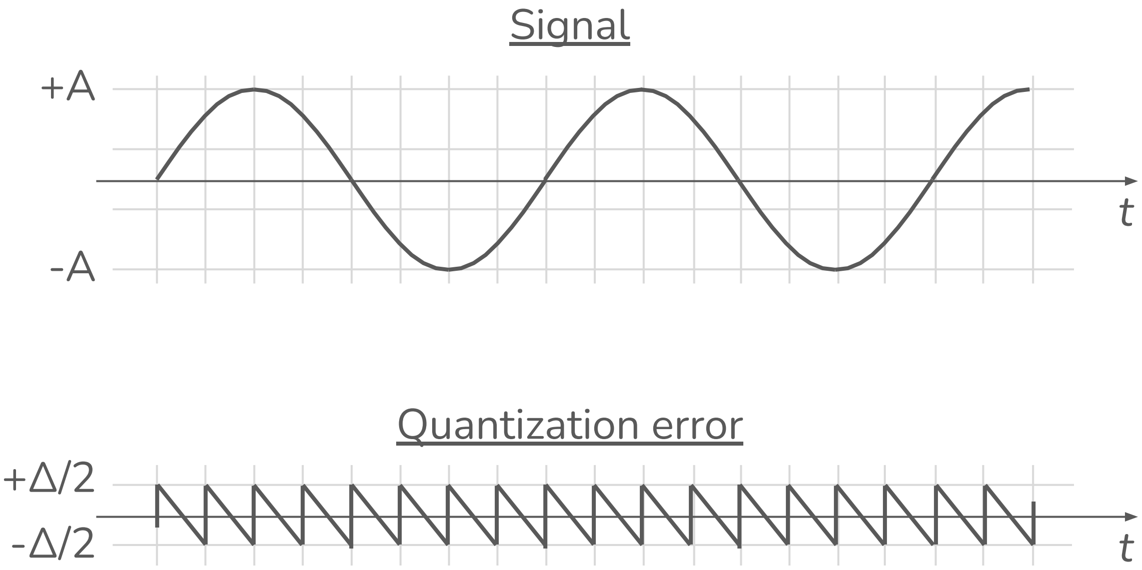
Quantization Error

- We treat quantization error as noise and evaluate a signal-to-noise ratio

Signal power = $A^2/2$

$\Delta = 2A/2^N$

Noise power = $\Delta^2/12$



$\boxed{\text{SNR [dB]} = 6 \times N}$

Quality of a Quantized Signal

$$\boxed{\text{SNR [dB]} = 6 \times N}$$

Every additional bit improves SNR by 6dB (4x)

The drawback is double the amount of data

Example: Radar Imaging System

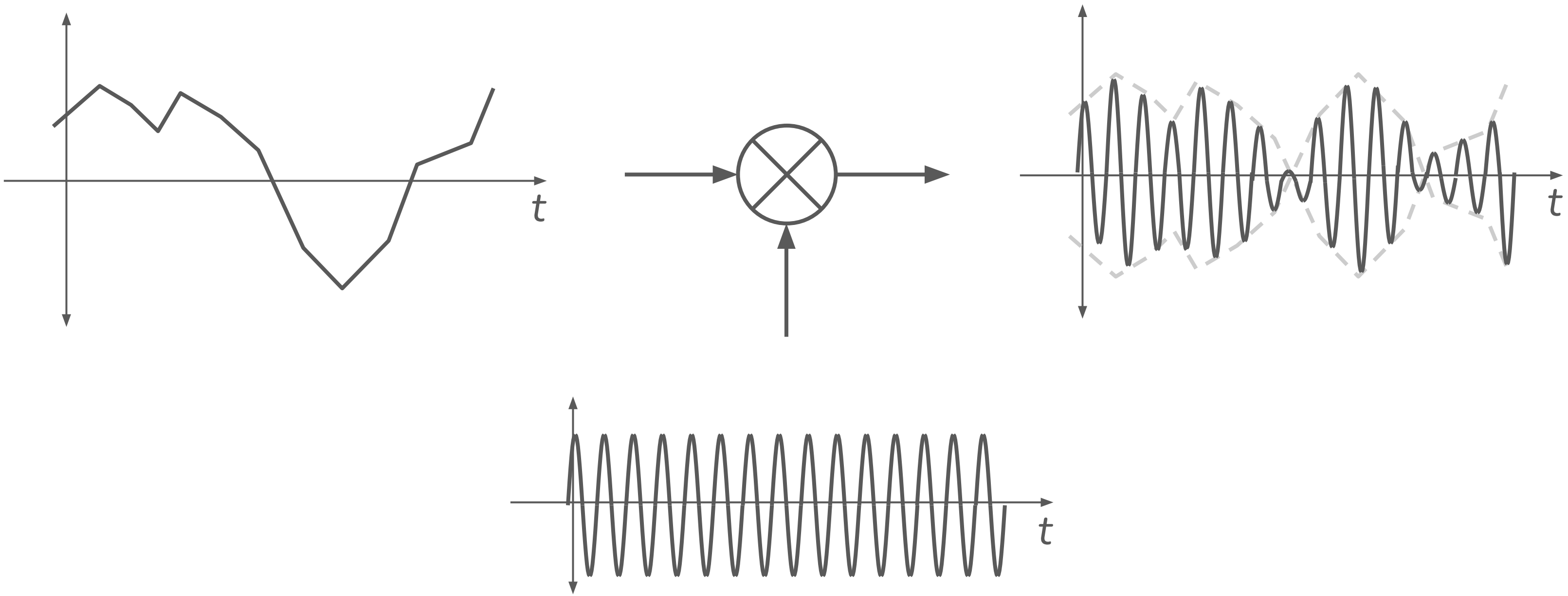
- Requirements:
  - Image resolution = 20cm
  - Image bit depth = 8-bit (256 shades of gray)
  - 4 minute collect per orbit
- Radar link needs to achieve SNR > 6×8 = 48dB
- Radar signal BW = c / (2 × resolution) = 750MHz
- Sample rate = 2×BW = 1.5Gsps
- Bit rate = 1.5Gsps × 8 bits/sample = 12Gbps
- Total data collected per orbit = 12Gbps × 4 min × 60 sec/min / 8 = 360GB

- So, one satellite produces 360GB of data per orbit!
- A constellation of 50 satellites would produce = 18TB per orbit!

Digital Communication

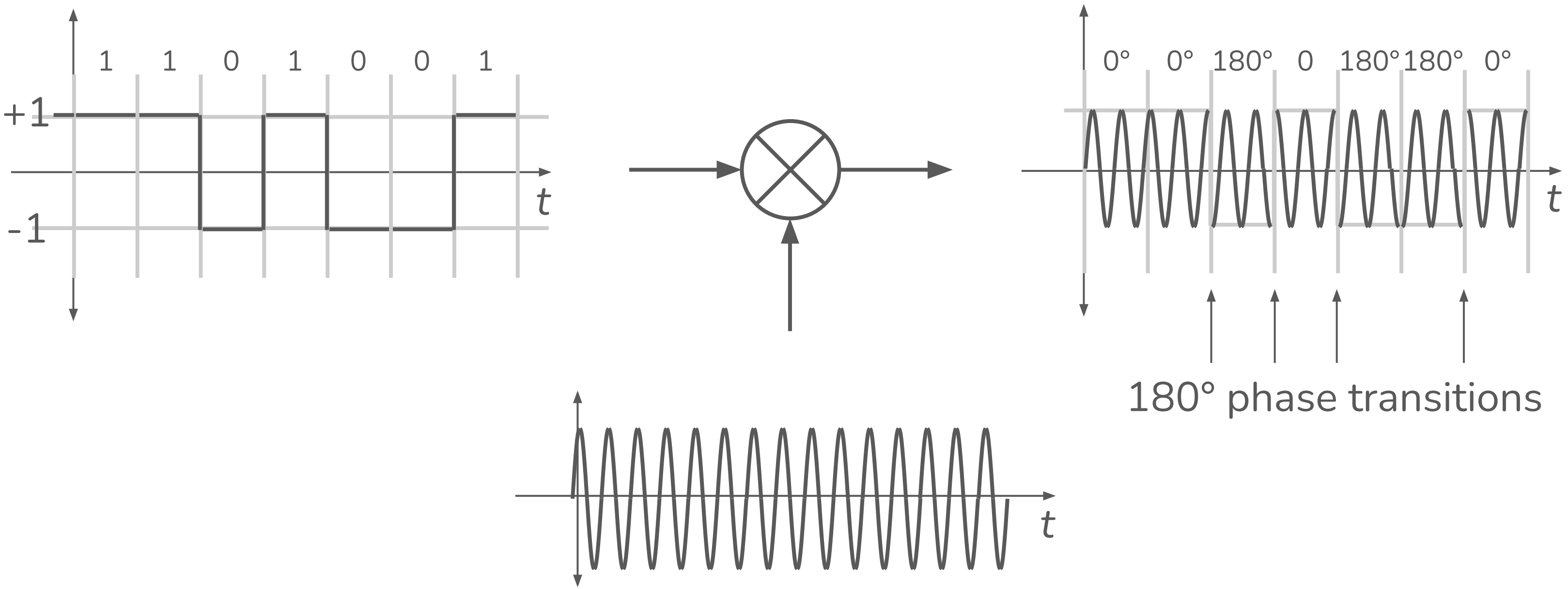
Recall Amplitude Modulation

- AM is a type of analog modulation

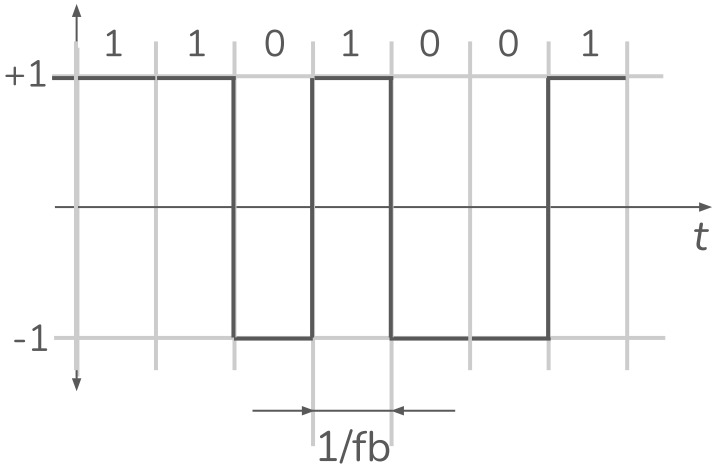


Digital Modulation

- Amplitude Shift Keying (ASK)



Amplitude Shift Keying (ASK)



BW = fb

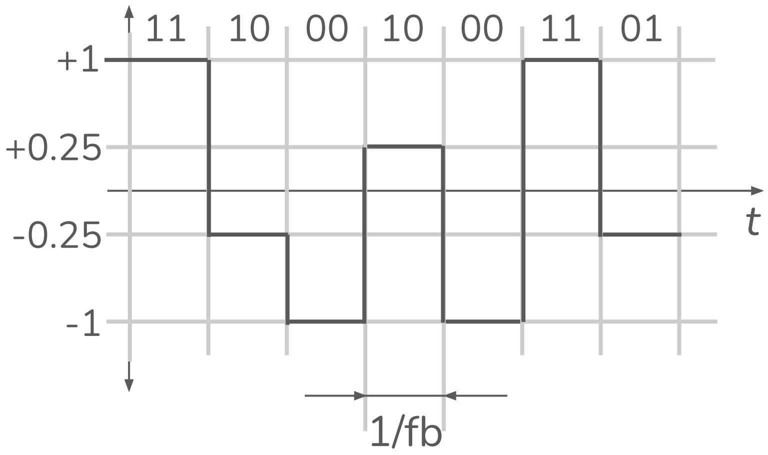
Bit rate = fb

But we can do better

- Better = cramming more bits into a given bandwidth
- Why is that better? Because spectrum is a valuable resource

4-ASK

- Group every 2 bits into a symbol → 2^2 levels → 4-ASK



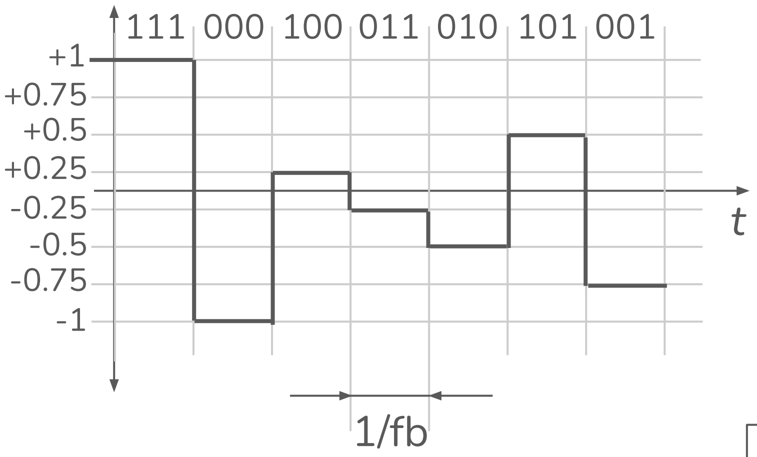
BW = fb

Bit rate = 2×fb

We've doubled the bit rate while using the same bandwidth

And we can keep doing that

- Group every 3 bits into a symbol → 2^3 levels → 8-ASK



Ethernet 100BASE-T uses 8-ASK modulation

BW = fb

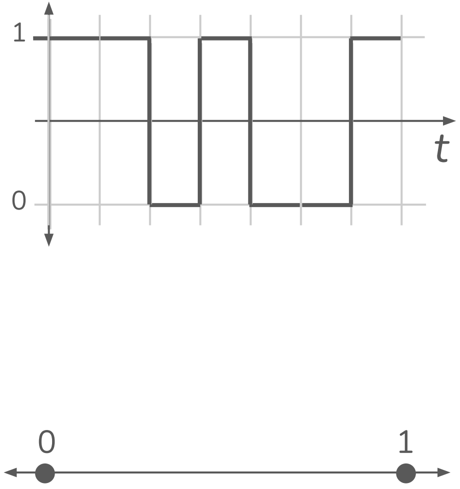
Bit rate = 3×fb

We've tripled the bit rate while using the same bandwidth

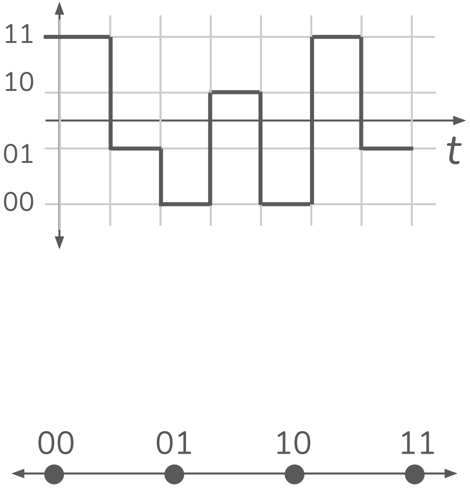
Constellation Diagram

- Constellation diagram = symbols arranged along the x-axis

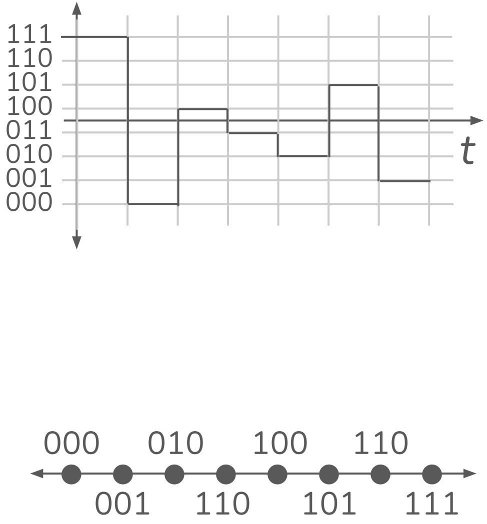
2-ASK



4-ASK



8-ASK

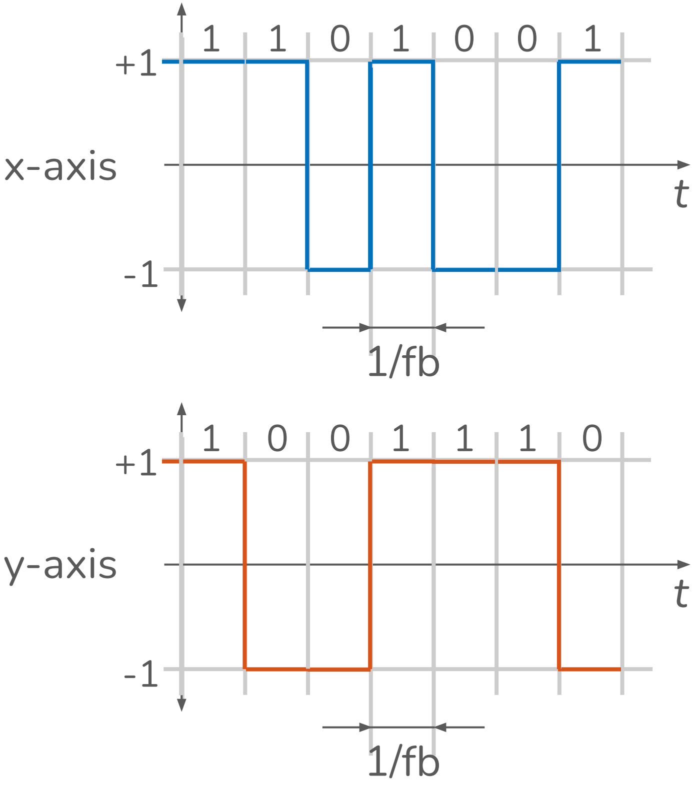


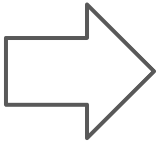
But we can do even better

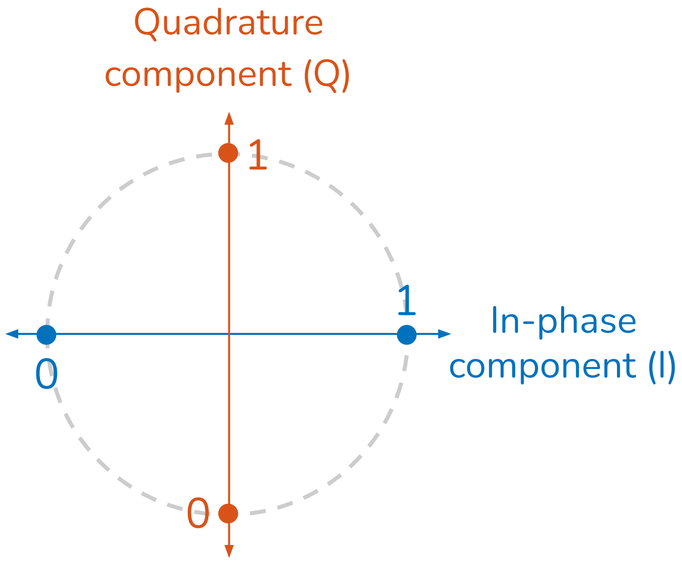
- Move from a one-dimensional constellation to a two-dimensional constellation

Two Dimensional Constellation

- 2-D 2-ASK





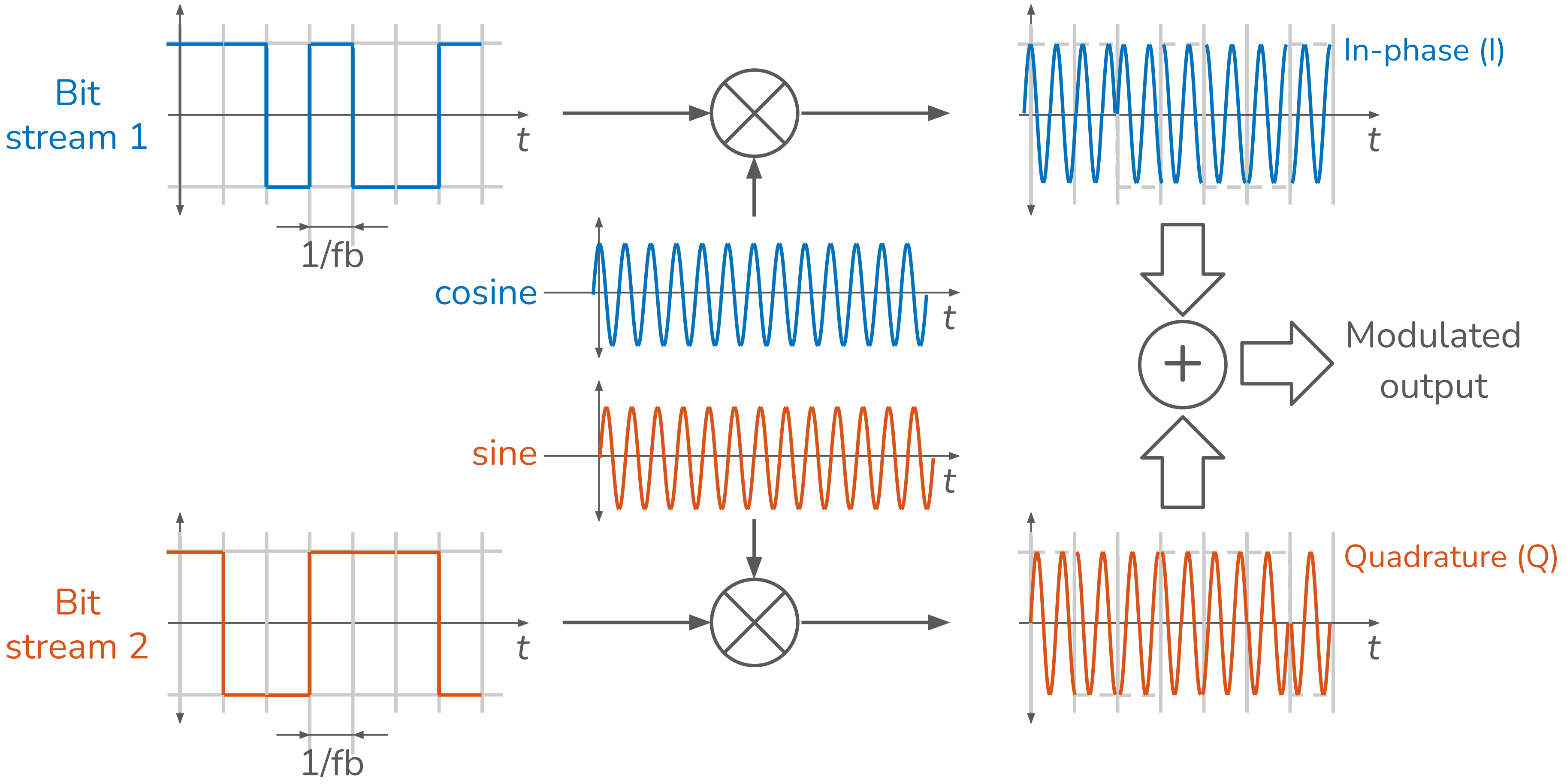


Bit rate = fb

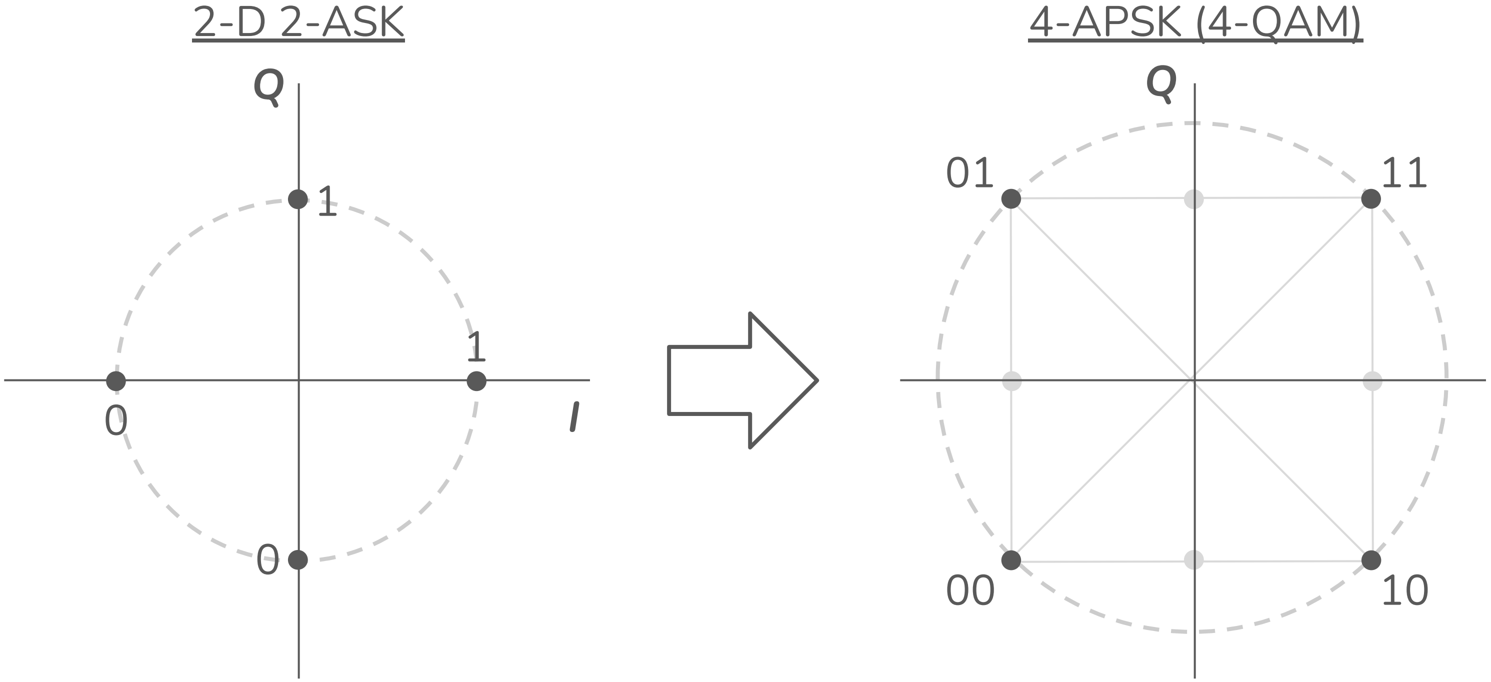
BW = fb

We've doubled the bit rate relative to 1-D ASK

How is that implemented in practice?



The actual 2-D constellation is a phasor addition

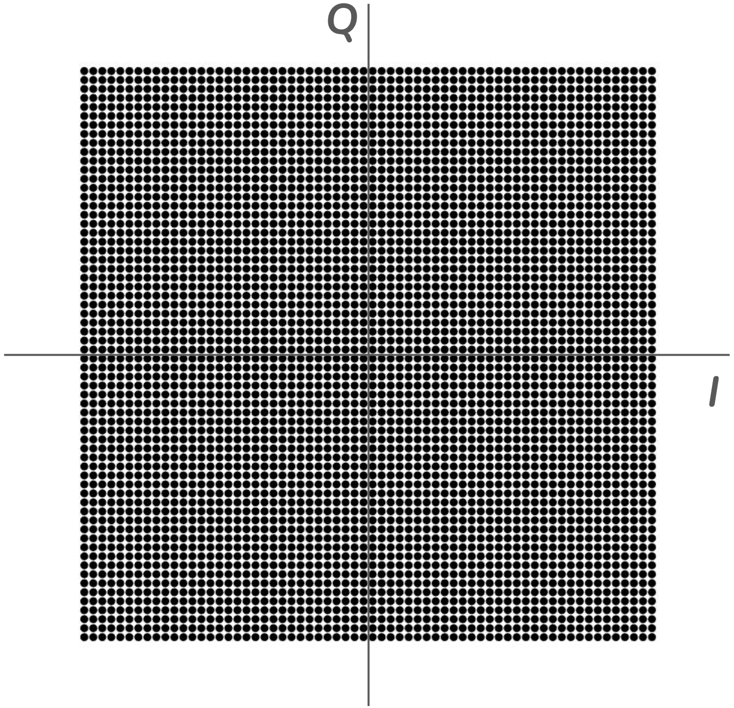


Also known as
Amplitude phase shift keying (APSK)
Quadrature amplitude modulation (QAM)

Some Constellation Examples

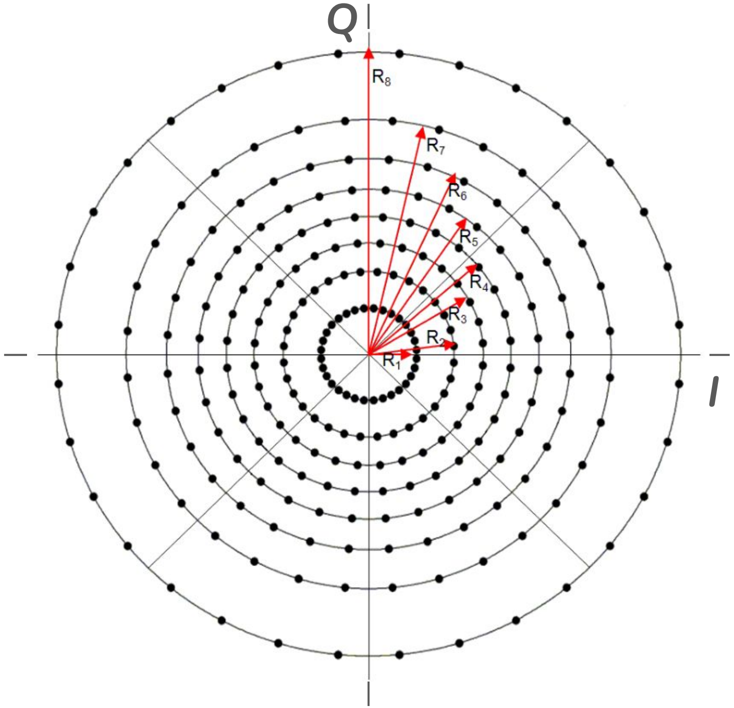
WiFi 4096-QAM

12 bits per symbol



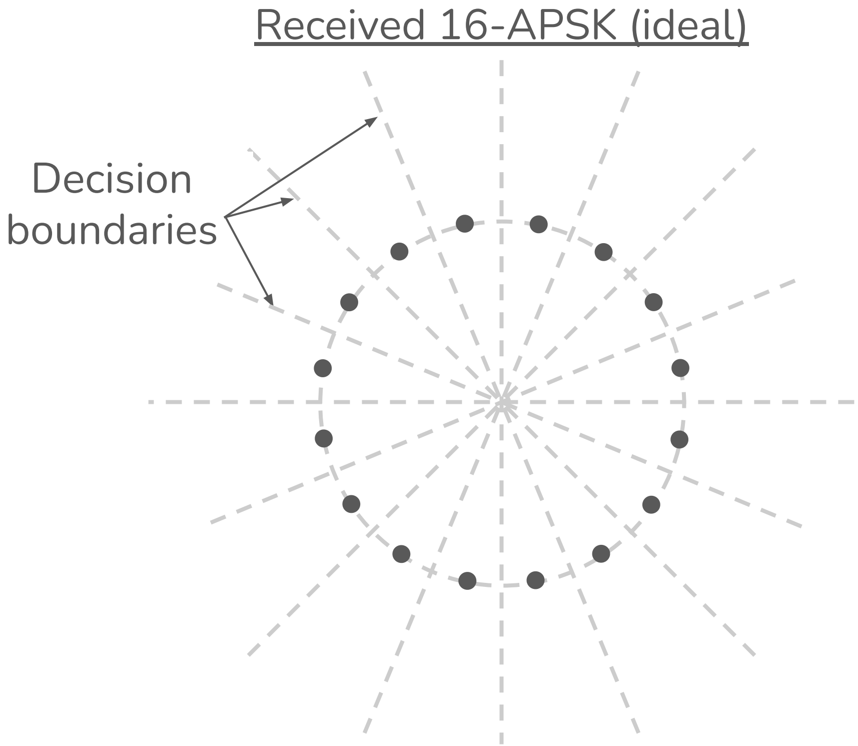
DVB-S2X 256-APSK

8 bits per symbol



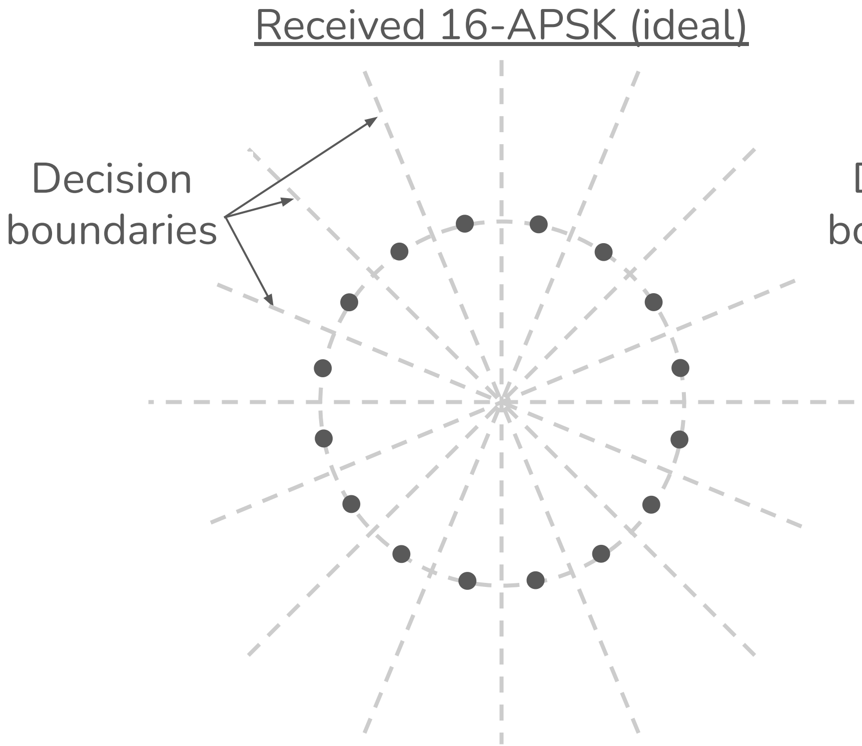
What’s the limit on packing bits?

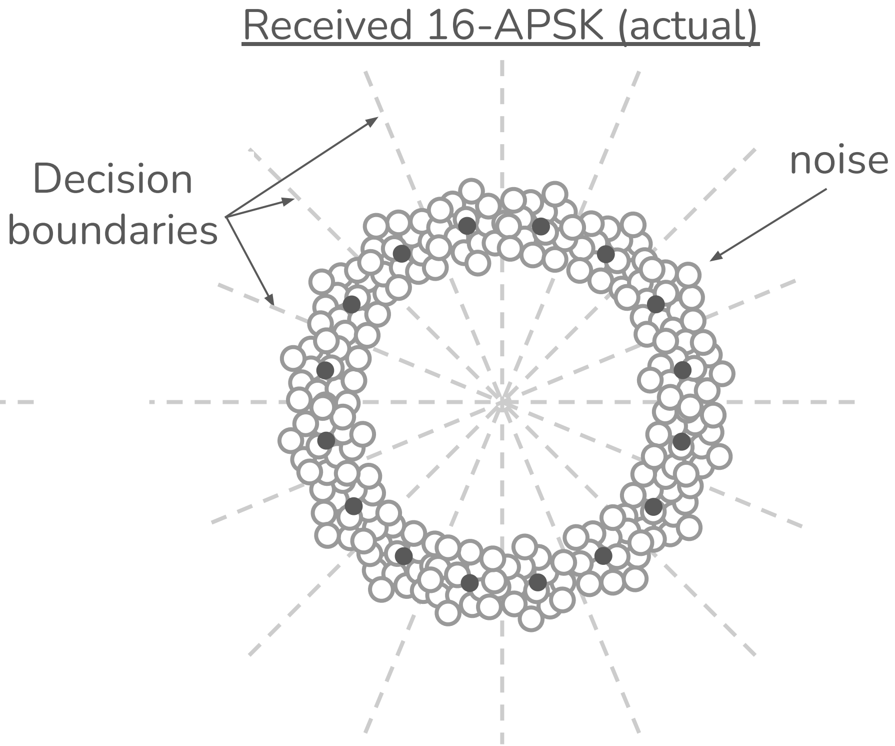
- Realize that the receiver decodes bits by making a decision on the received symbols



What’s the limit on packing bits?

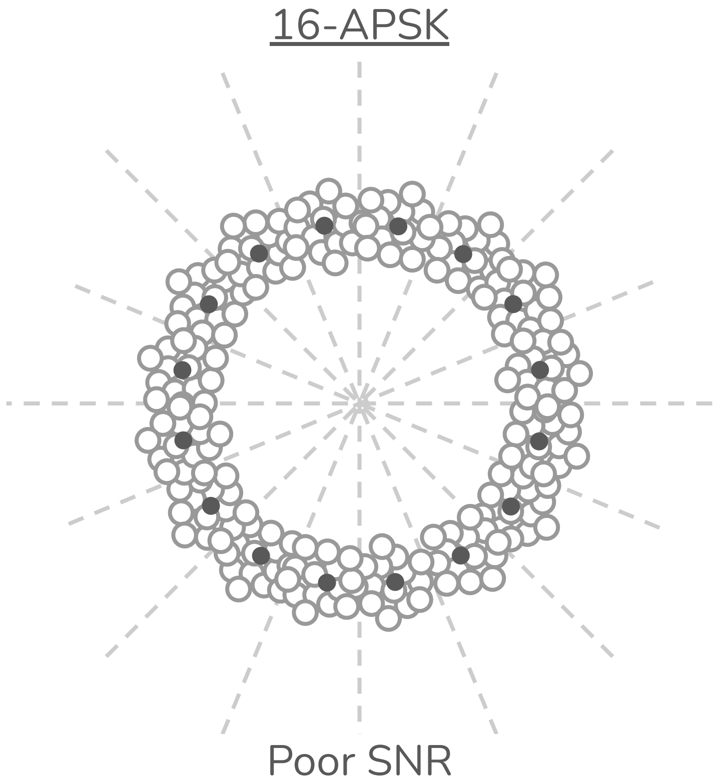
- Noise sets the limit on packing density because it introduces uncertainty → bit errors

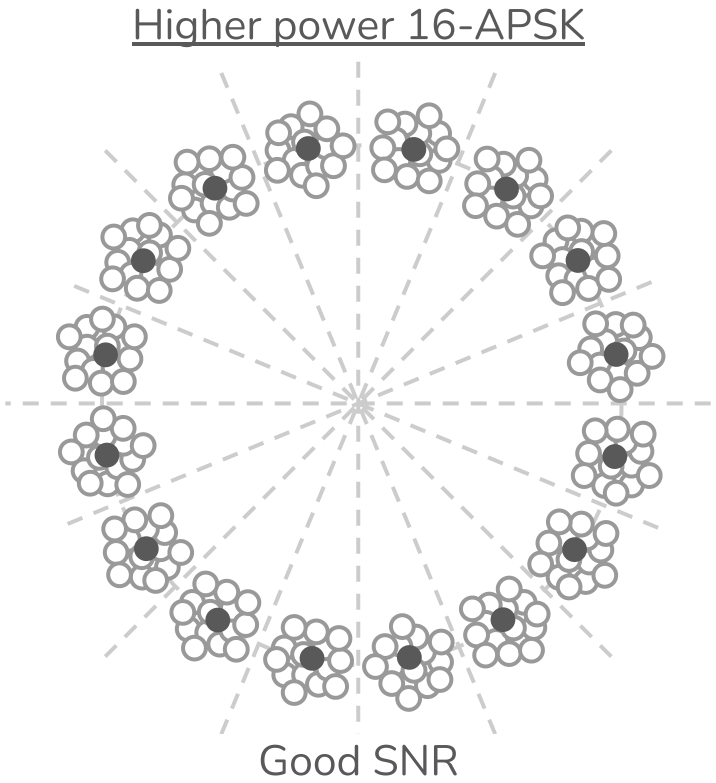




What’s the limit on packing bits?

- Packing more bits requires more signal power to differentiate between symbols





Example: Satellite High-Speed Downlink for Radar

- DVB-S2X standard
- Modulation: 256-APSK (8-bits per symbol)
- Available bandwidth = 375MHz
- Data rate = 375MHz x 8 = 3Gbps
- DVB-S2X efficiency = 65% (error correction bits, frame headers .. etc)
- Useful data rate = 3Gbps x 65% = 1.95Gbps
- Assuming 8-minute pass per ground station
- Data downloaded per orbit = 1.95Gbps x 8min x 60sec/min / 8 = 117GB

- Recall: A 20cm resolution radar produces a bare minimum of 360GB of data per orbit!

Thanks!