"EE 101"

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Lecture 3 V1.0

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What is the EE problem?

Get some data across a link, or “channel”.

- Not a network, just a link.
- Could be a wire, a fiber, radio, or something.

The space of design--multi-dimensional optimization:

- Bandwidth and distance
- Cost
- Power
- Efficiency (what does this mean?)
- Robustness and resilience

What are we sending?

Computer systems represent data as bits, so we send bits.

Other systems send analog signals, or digitized analog systems (bits, usually).

- So no single answer.
- A brief digression into sampling.

Do we always send bits?

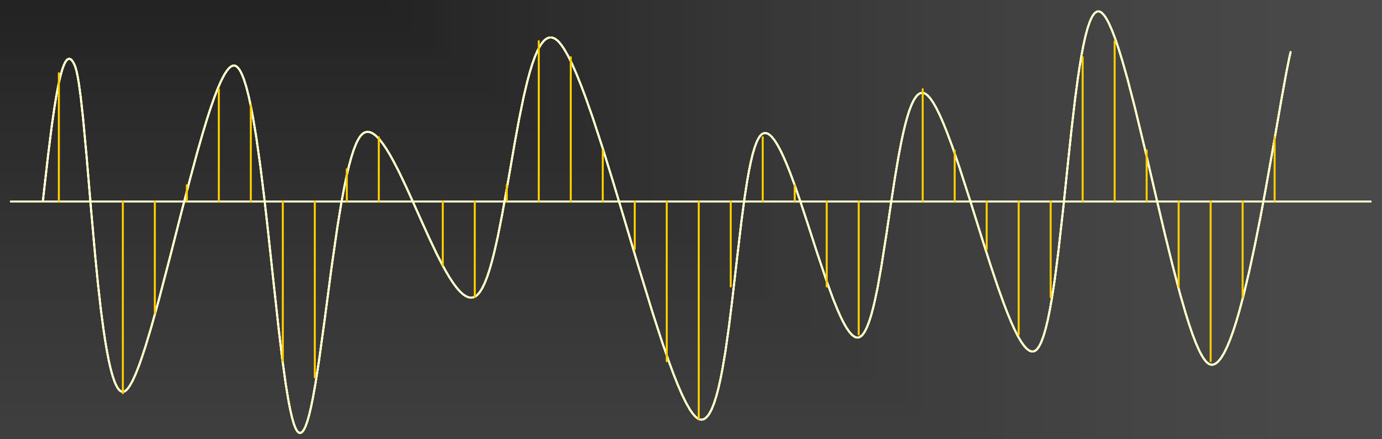
- No. That is a “recent” idea.
- Television, radio, etc are “analog” signals.
- Amplitude modulation (AM) : the amplitude of the signal at any moment represents the amplitude of the data being sent.

But we can convert

To "digitize" an analog waveform.

- Find the highest frequency in the signal.
  - Or filter to make it so.
- Measure the amplitude at (at least) twice that frequency (the Nyquist rate).
- Those two values are sufficient to recreate the waveform.
  - Subject to the precision of the measurement.

Example:



Sample and digitize

Represent each sample as an integer of some precision, send the numbers.

Example: 4 kHz signal (telephone), 8 bits per sample (256 values) -> 64 kb/second.

Example: 20 kHz, two channel (hi-fi stereo), 16 bits per sample, 1.28 mb/second

- CD sample rate is 44.1 kHz, 1.4122 mb/s

So assume we are sending bits

First question: what does a bit look like?

- Lots of representations: low/high voltage, on/off light, high/low tone, N/S magnetic spin.

Picking the rep is part of the design.

Try a simple idea to send a bit

Take a wire.

Send DC voltage for 1, no voltage for 0.

Reconsider: means sending average of 1/2 voltage, so net current flows.

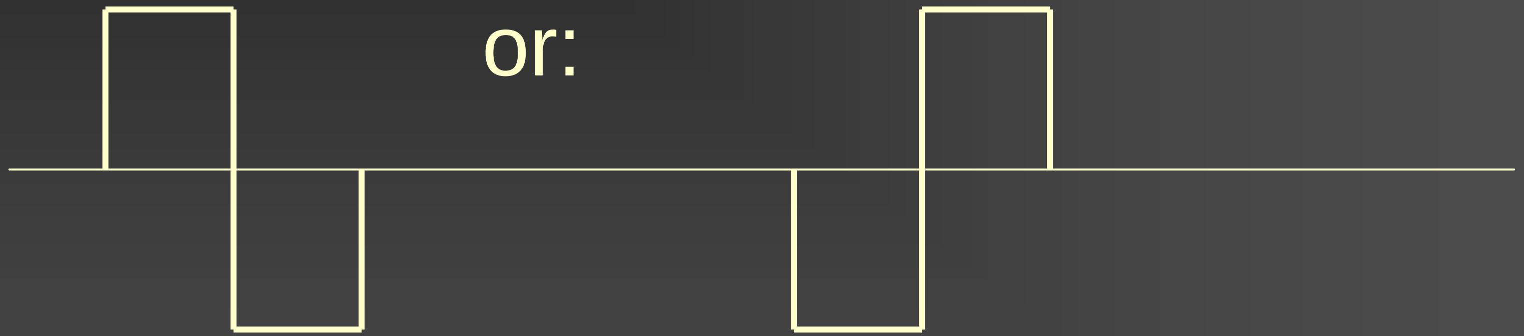
Send + DC voltage for 1, - DC voltage for 0.

Simple, low cost, does not go very far, works.

- 10 mb/s ethernet (sort of)

Early ethernet

Send either:



or:

(Sequence of 1’s or 0’s does not lead to continuous current.)

How can we evaluate this?

Capacity C, bits/second.

Distance

Cost

Let’s talk about distance

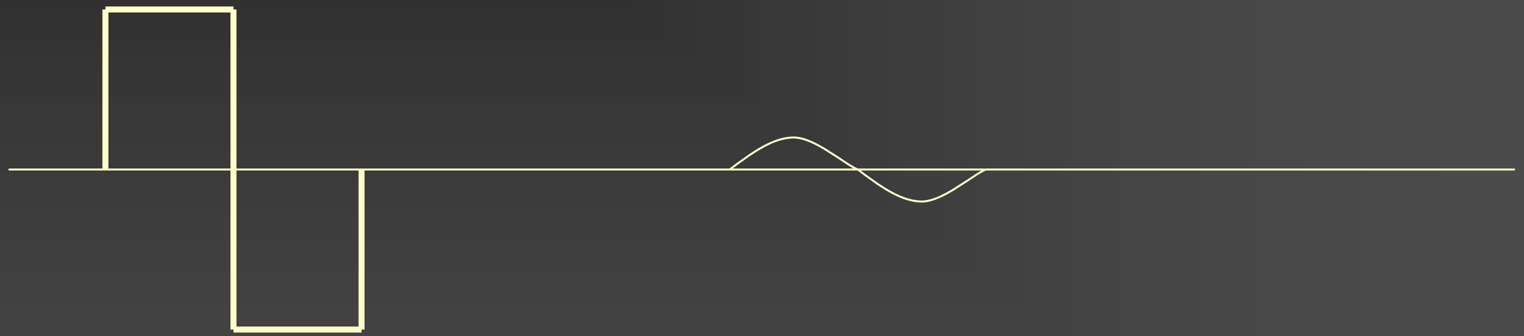
First digression into EE:

What happens to a signal as it goes down a wire?

- It gets weaker.
- Crisp transitions get vague.
  - High-frequency attenuation.

Crude visualization

What goes in: What comes out:



After a while, cannot find the signal in the noise. So the representation interacts with distance to determine the region of utility.

How could we improve this?

Go further, or send more bits, or something.

One option: improve the wire.

- CAT 3, CAT 4, CAT 5, CAT 6, etc.

What are they doing?

- Reducing loss.
  - Make the signal at the receiver bigger.
- Reduce high-frequency attenuation.
  - Make the signal more well-defined.

So we have a clue to design

- Wires can carry certain frequencies. This is the “bandwidth” of the wire.
  - Bandwidth B (measured in Hz) is not Capacity C (measured in bits/second).
- Higher frequencies attenuate, and distance makes it worse.
  - Higher speed ethernet does not go as far.

Another idea--better representation

A short history of dialup modem design:

- The channel has a bandwidth of about 4 kHz.
- So signal must have a frequency profile that fits inside that envelope.
- How to do this?

Instead of two voltages, send:

- Two frequencies? FSK -> 110 b/s in 1960's
- One frequency but shift the phase? PSK
- Why just two? Aha!

Multiple bits per symbol

2 bits per symbol: 4 symbols

3 bits per symbol: 8 symbols

And so on…

How to create multiple symbols?

Adjust the:

- frequency
- phase
- amplitude

Def: Baud--symbols/second. Not bits/second

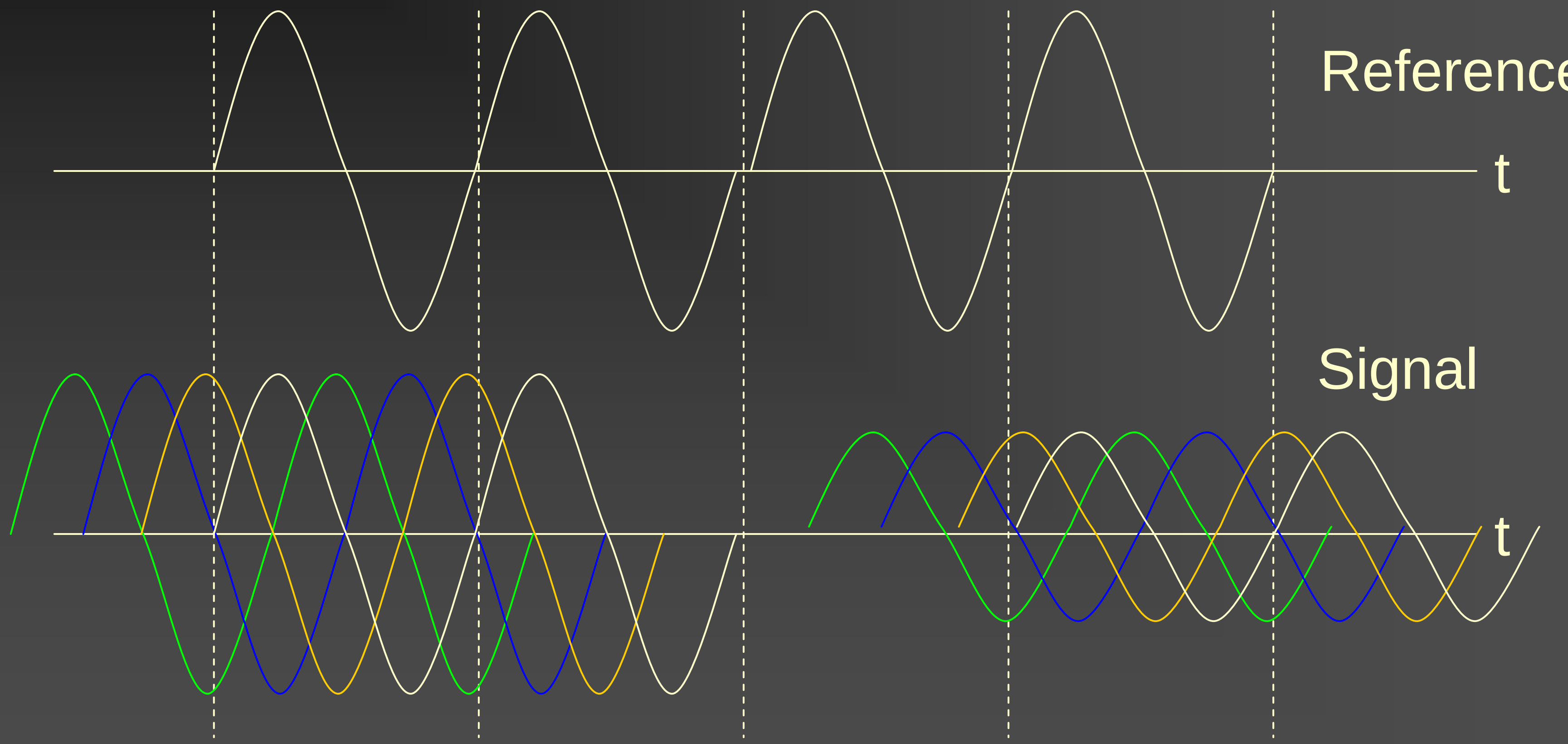
An example: QAM

Quadrature Amplitude Modulation.

“Quadrature” describes a way to talk about variation in the phase.

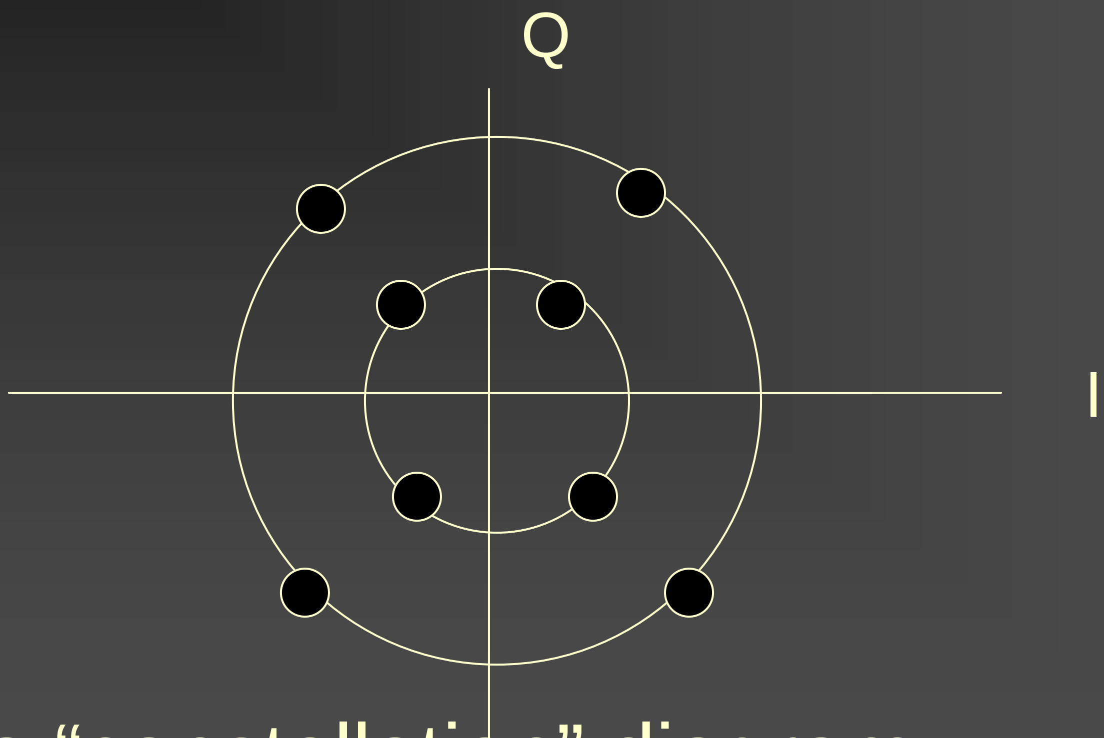
- With respect to a reference, a signal can be “in phase” or “in quadrature” which is 90 degrees off.

Four phases, two amplitudes



A different representation

Polar co-ordinates



This is a “constellation” diagram.

QAM state of the art:

256 QAM

16 values for I

16 values for Q

256 symbols, which means

8 bits per symbol

A figure of merit:

A circuit has bandwidth B, measured in Hz.

We devise a scheme with some capacity C, measured in bits/second.

Express the efficiency as C/B, or bits/second/Hz (b/s/Hz)

- Original modem 110 b/s 4 KHz, .0275 b/s/Hz
- Current modem 56 kb/s, 14 b/s/Hz (this is impossible in general, and requires magic)

Factor of 509 improvement

Can we just get better?

Shannon gave us the theoretical limit, in terms of capacity C, bandwidth B, signal power S and noise N:

$$C/B = \log_2 (1 + S/N)$$

- This is hard to derive but easy to think about.

Case 1: high signal to noise:

$C/B = \log_2 (S/N) = 3.3 \log_{10} (S/N) = .33$ dB S/N

So 30 dB channel -> 10 b/s/Hz

40 dB channel -> 13 b/s/Hz

Another design clue

- Turning up the power and “blasting away” is an inefficient way to go.
  - That “log” is a pain. 10x power means only +3 improvement in b/s/Hz.
- Much better to increase the bandwidth.
  - Double the bandwidth, same power, double the bits/second. (ignoring increase in noise.)
  - So go to the FCC and fight for spectrum.

What about radio?

All this applies.

- Divide the spectrum up into frequency bands.
  - Think TV, FM, AM, etc.
- Use some scheme like QAM in your band.

Current schemes come close to the Shannon limit.

But radio is noisy, so b/s/Hz tends to be worse than over a wire (Duh!)

State of the art

TDMA cellular, 48 kb/s over 30 kHz channel, or 1.6 b/s/Hz.

- Power limited (cell phone battery).
- Spectrum limited (want to carry lots of calls at same time).
- Noise limited.

Television: analog to digital

Old way--analog

- Divide the spectrum into 6 mHz bands.
- Fit one TV signal into each band.
  - View the picture as a series of horizontal lines
  - Sweep across the lines in time
  - Signal at each instant is the brightness of that point.

The digital version of TV

New way--digital

- Keep the 6 mHz allocation
- Cable: use 256 QAM, get about 6 b/s/Hz, or 36 mb/sec
- Over the air: more noise, so perhaps 3b/s/Hz.

How many bits to carry a TV picture?

- “It all depends”, but about 1 mb/s
  - Get 4 or 5 digitized channels in one band

Why is the phone so limited?

Where did that 4 kHz limit come from?

The wire?

- Nope. The wire can do better than that?

The switches?

- Not the old ones. Relays have great bandwidth.

It is the digital backbone.

- The insides of the phone system are all digital.
- Nyquist sampling *requires* that you filter before you sample.

Things can get complex

Think about computer communication over the phone system.

- Encode the digital stream into a 4 kHz limited analog signal.
- Send that to central office, where…
- It is digitized as 64 kb/s bit stream,
- Which is then encoded and send over high-speed circuits.

So how does DSL work?

DSL: digital subscriber loop.

Just use the wires, not the switches.

Push the limits of the wires.

- Very dependent on distance and quality.
- 1 or 2 mb/s over 15,000 feet.

Use new switching equipment.

- DSLAM, or DSL access module.
- Must be in *each* central office.

So where to decode?

Use DSL as example.

When data goes to the central office, what then?

- Sample the DSL signal, digitize, encode and resend.
- Decode the DSL to extract the bits, then send in some other format.
  - That is the Internet way--at each forwarding point, extract the packet, then recode for the new medium.

Different ways to share?

Dividing spectrum up into frequency bands is not the only option.

- Made lots of sense with simple, pre-digital radios.

Go back to Shannon. For given power, best C/B improvement is wider spectrum.

So perhaps we could all use the same spectrum and share in some other way?

Spread spectrum

General idea:

Instead of squishing my signal into a narrow frequency band.

Intentionally spread it out across a wide band.

Two questions:

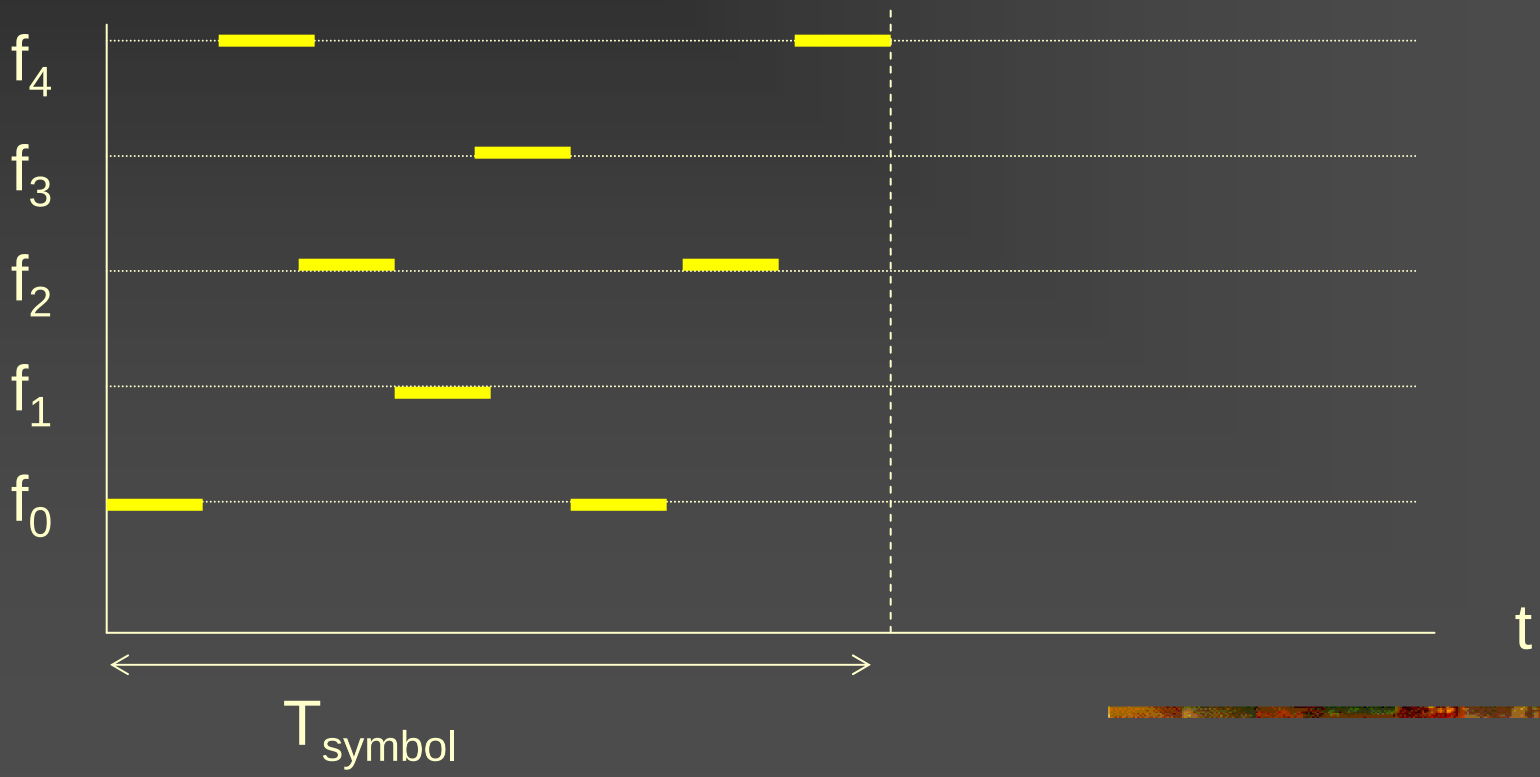
- How?
- Is it really a good idea?

History

- This idea is older than Shannon.
- Original idea was to hide the radio signal from enemy detection (assuming a narrow-band receiver).
- WW2, patent by Hedy Lamarr and George Antheil, 6 years before Shannon's result.

Frequency hopping

Modulate carrier, then shift it around during the symbol time. The pattern of frequencies is the “code”.



Thinking about spread spectrum

The receiver can follow the signal if it knows the code. Otherwise, hard to find the signal in the noise.

- CDMA--Code division multiple access.

There are other ways to spread the signal.

If the signal is spread out enough, then on the average, S/N is less than 1.

- The improvement from knowing the code is the “processing gain”, measured in dB.

Back to Shannon

- $C/B = \log_2 (1 + S/N)$
  - Where total noise $N = N_0 B$
- If $S/N < 1$, expansion of $\text{Log}\,(1+S/N) \propto S/N$
  - So turn up the power?
- But N is now the signal from the other senders.
  - This is not as efficient as frequency division.
  - Noise proportional to signal: don’t turn up power
- But N is not Gaussian white noise.
  - So Shannon’s limit does not apply.
  - That other “noise” is signal, so process it

So why do spread spectrum?

Difficulty of interception and detection.

"Soft" sharing.

- Instead of rigid frequency bands, more or fewer shares depending on current conditions.

Easier to exploit the power of digital signal processing.

The ultimate…

What is the spectrum of a pulse?

It is spread out across a wide band of frequencies.

- Think about a lightning bolt.

So send a signal by emitting pulses.

Ultra-wide band (UWB)

- Is this cool, or stupid?

And other ways to share

Share over time--taking turns.

- Static shares
- Listen before sending
- Listen while sending

Share in space

- TV and radio in different cities
- Cell towers
- 802.11

Many patterns of communication

One to one:

- A phone call

One to many:

- Radio and television
- 802.11 (pattern of sharing, if not comms)

Many to many:

Review--what is the point

Goal is to communicate
- Over a channel of some sort.

With various requirements and constraints
- Distance
- Capacity
- Cost
- Efficiency: power, use of spectrum

Engineers spend lots of time devising solutions.

Summary: “EE” rules of thumb

Coding:

- Over a wire: 6 b/s/Hz is pretty good.
- Over the air: 2 b/s/Hz is pretty good.
- With bad noise: 1 b/s/Hz is not bad.

Sampling:

- 8 bits/sample x 2 samples/Hz = 16 b/s/Hz

So why digital?

- Compression, clever sampling, etc.
- Usually better in practice.

Why is this relevant to the class?

A wire is a private affair (usually).

Spectrum is more public.

- Most countries, as matter of policy, regulate its use. In US, FCC and NTIA.

Regulation centers on who can use, and how to divide it up.

- In other words, how to share.
- So regulation constrains the technical options.
- By tradition, allocate frequencies. See NTIA chart.
- But this is not the only way, as we have learned.

Propagation

- A final technical issue: what happens to radio signals as they radiate.
  - We looked at propagation along a wire: signals get weaker and lose the high frequencies.
- Radio is like light (sort of).
  - Signal strength falls off as $1/d^2$ (or worse)
  - Signals reflect
  - Signals interfere at the receiver (but not in free space)
  - Fade varies over time
- Different frequencies behave differently.
  - Lower frequencies refract more.

Antenna design

- Use multiple antennas to deal with interference (curing “deep fade”)
- Use multiple antennas to create multiple paths.
  - This seems like magic.
- As frequencies go up, antennas get smaller.
  - But receive less power.
- This is a golden age for electrical engineering.
  - Higher frequencies, digital processing, cheap silicon, better theory.
  - Creates lot of tension for regulators.

When is an antenna…

not an antenna?

- When it is a wire.

When we *want* the signal in the form of electromagnetic radiation, we call the wire an antenna.

When we *don’t* want the radiation, we call it

- Cross talk
- Leakage
- Interference.

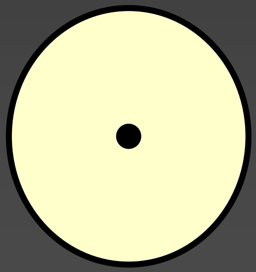
In this respect, wires are *not* private.

Designing better wire

Keep the signal inside when you want it inside.

Avoid loss (attenuation).

Have a high bandwidth.



Co-axial cable
A grounded sheath to keep the signal from leaking out

Twister pair
Reduces radiation, inexpensive
Shielding makes it worse.

How about fiber?

- Wonderful signal to noise ratio.
- Very little signal loss, compared to copper.
- So why try for spectral efficiency?
  - Typical modulation: light on/off.
  - Fiber is a cost-constrained design space.
    - High speed lasers are costly.
    - Long distance (high power) lasers are costly.
- For more efficient use of fiber, use simple frequency (color) division.
  - Dense wavelength division multiplexing DWDM
- Only now beginning to see more complex modulation schemes.