OAK RIDGE National Laboratory

Man or Machine?: Developing a "Turing Test" for Radio Intelligence

Dr. Adam L. Anderson
Oak Ridge National Lab
Tennessee Tech University

GRCON '19

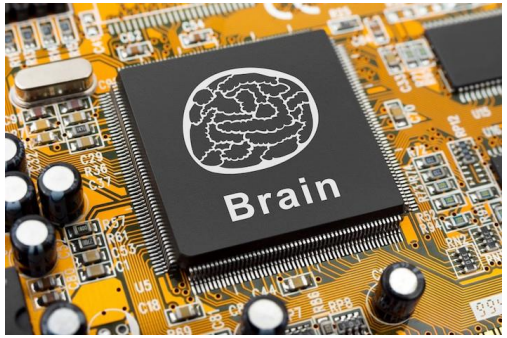
ORNL is managed by UT-Battelle, LLC for the US Department of Energy

U.S. DEPARTMENT OF ENERGY

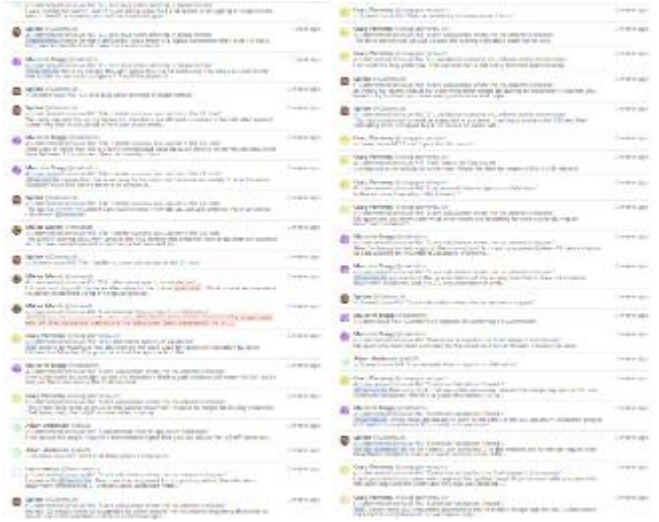
AI/ML in Comms

<u>Competition Fantasy</u>

Adding intelligence to the AD9361 chip.



vs.

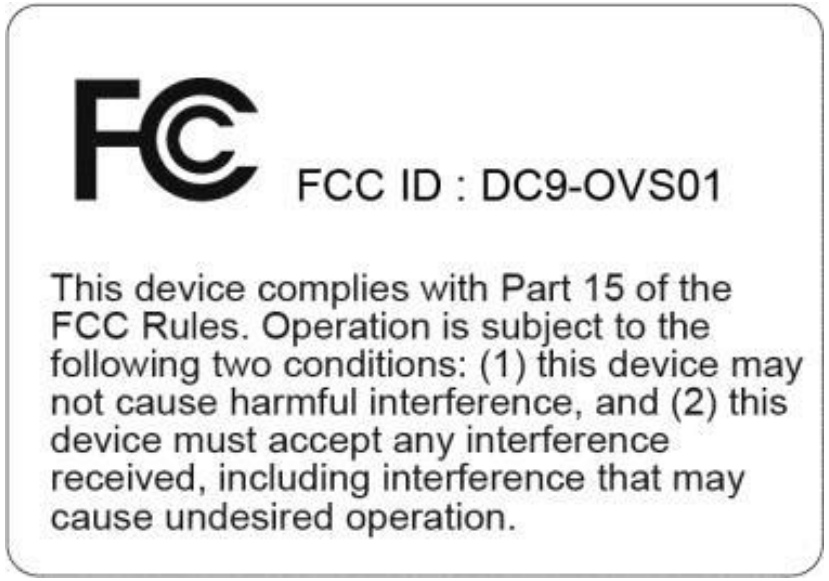


<u>Competition Reality</u>

Lots and LOTS of arguments about compliance.

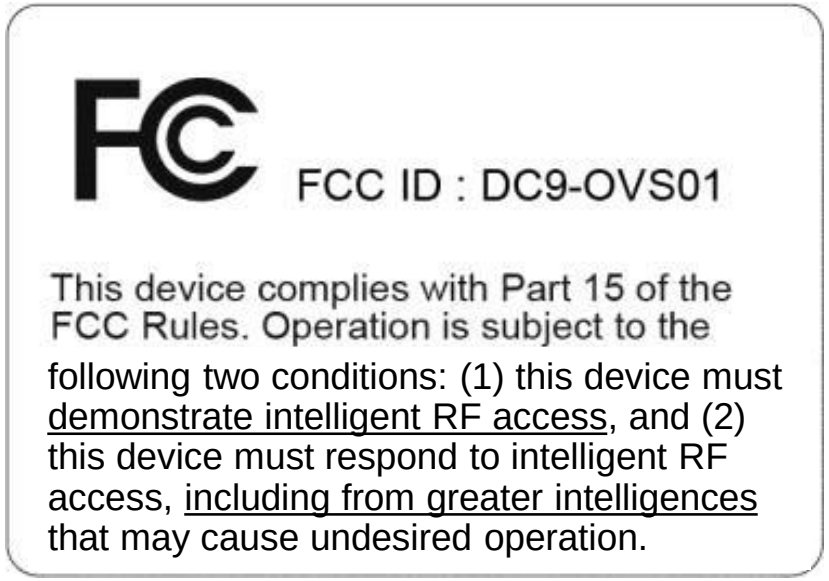
Age Old Problem: Accessing Congested Spectrum

20th Century Wireless



Lower your power.

21st Century Wireless?



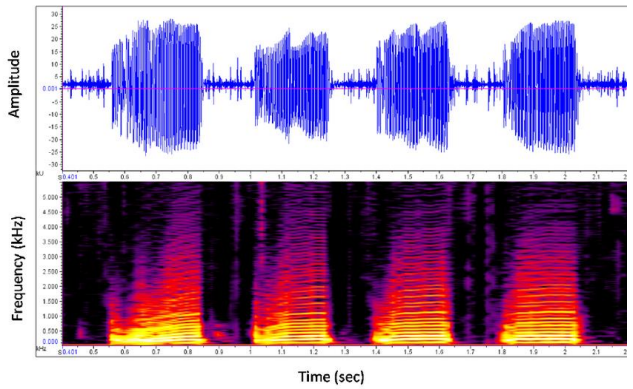
Increase your intelligence?

But what is radio intelligence?

Increasing Radio Intelligence

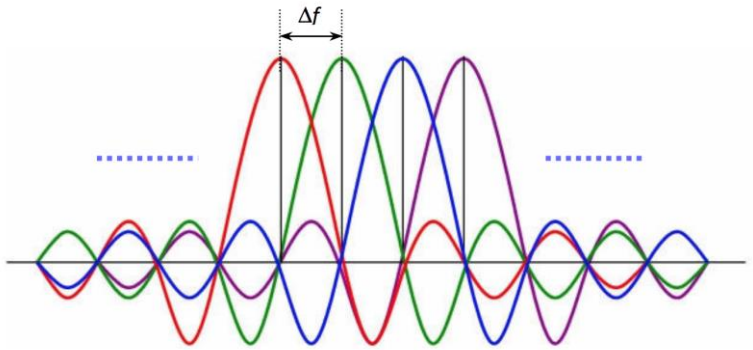
"Learning is the search of a parameter space in order to optimize performance."

Where/When to Transmit?



Make smart decisions on:
- Frequency
- Time
- Power

How to Transmit?

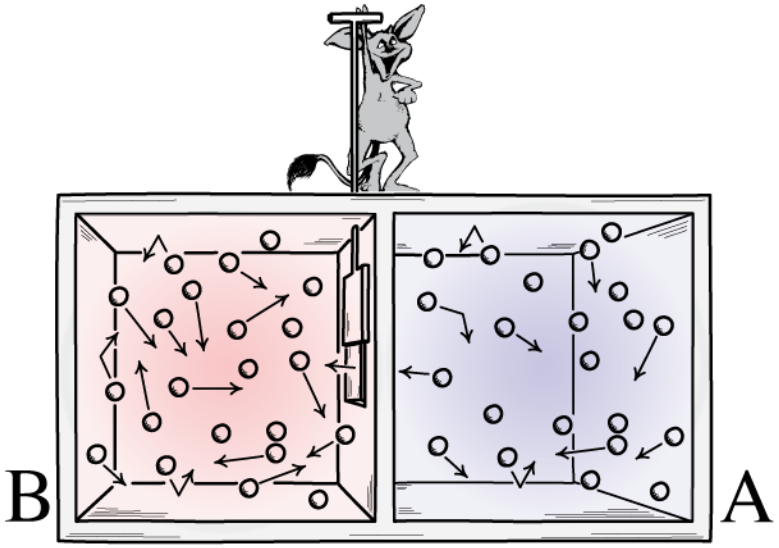


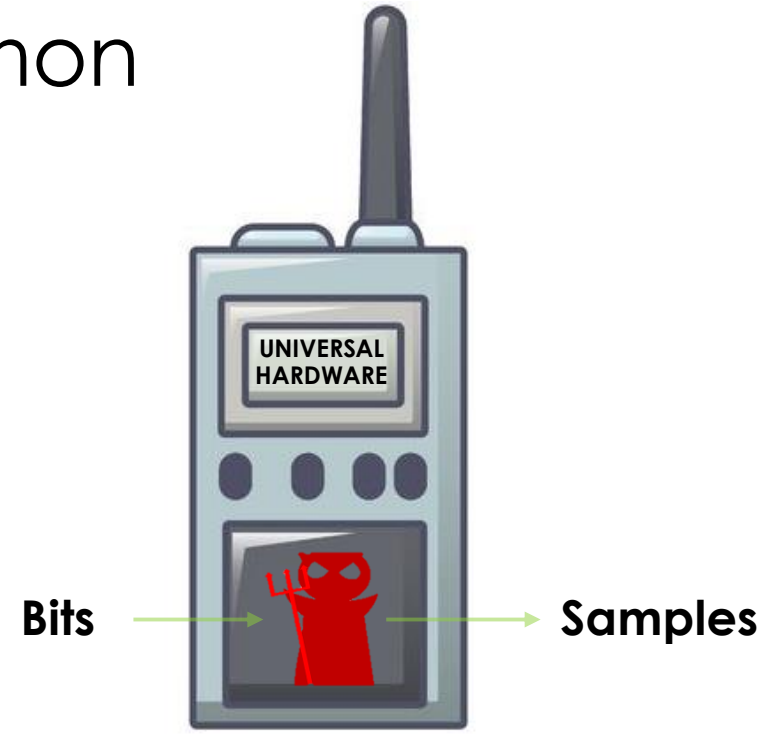
Make smart decisions on:
- Waveform
- Spreading / Hopping
- Anti-jamming

What to Transmit?

Make smart decisions on:
- Error-correction
- Encryption
- Cyber Security

Radio Intelligence with Comm's Demon





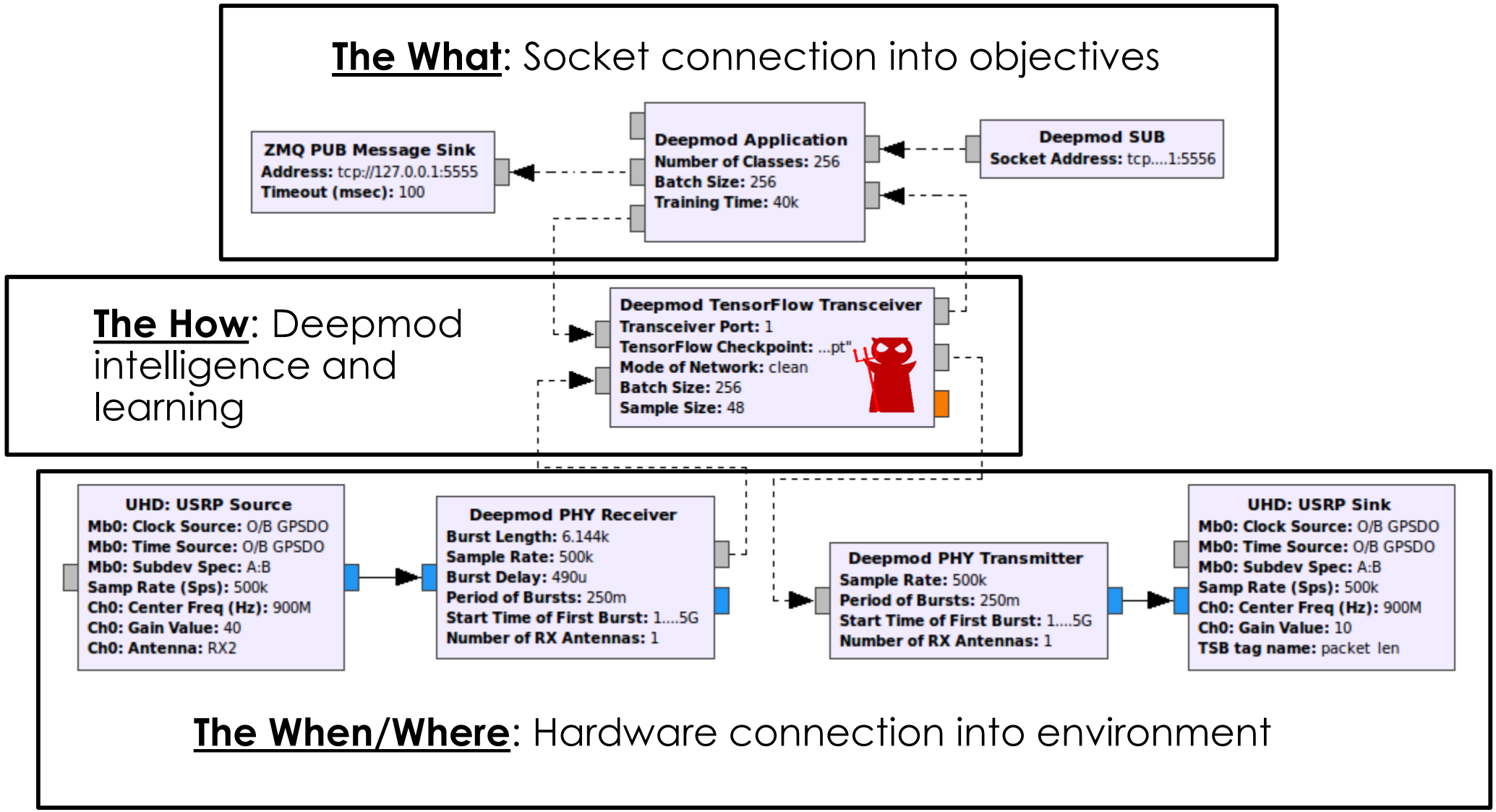
Maxwell's Demon

1. Hot and cold molecules exist inside a box
2. A "demon" manipulates a door to trap same type molecules on each side
3. Thermodynamics is violated
4. Physicists freak out

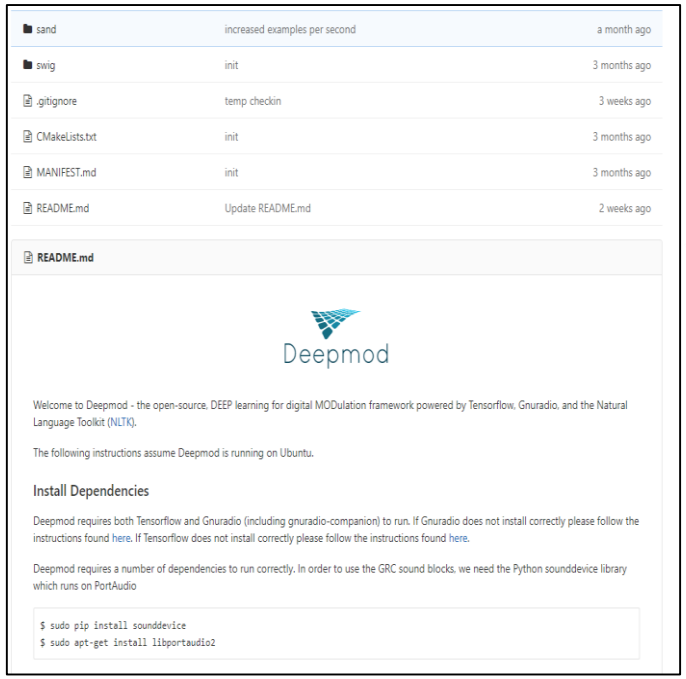
Comm's Demon

1. A device with universal hardware is placed in an environment
2. Objectives are given to the "demon"
3. The demon rederives all formerly human-invented processing for that environment
4. Comm's people disbelieve

Deepmod: Summoning the Demon

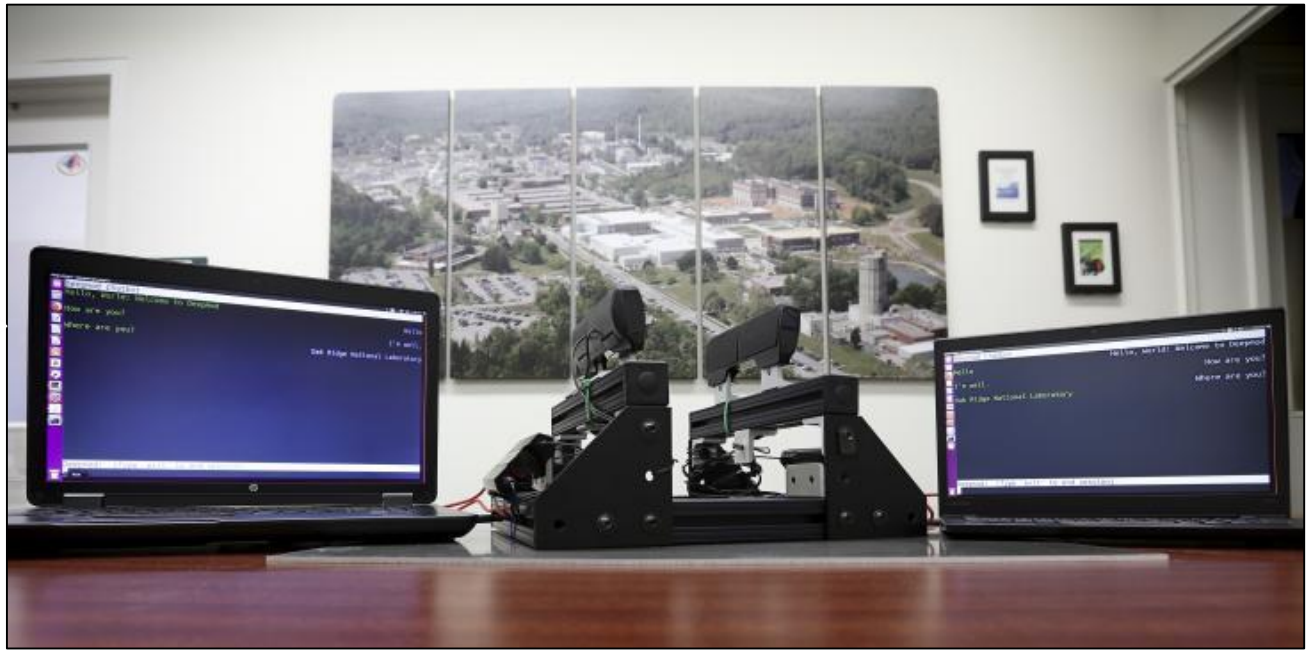


2018 Deepmod: Acoustic Channel



Software

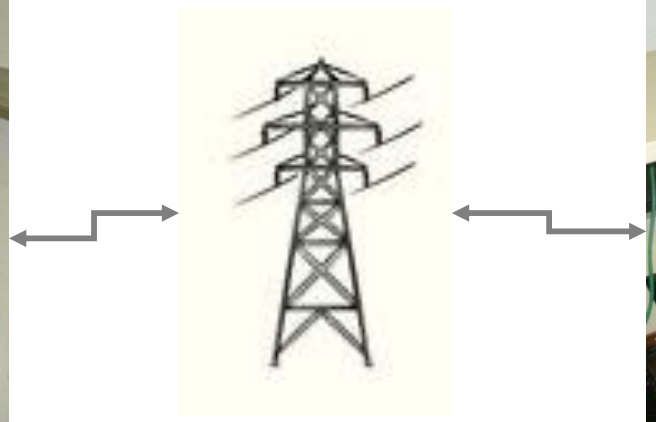
Hardware

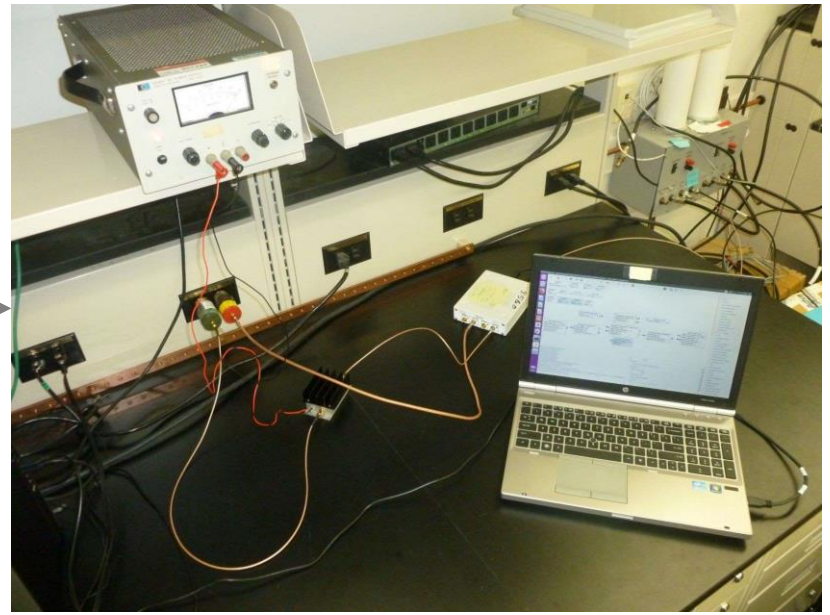


Demo "Machine Speak"

- Deep convolutional neural network autoencoder
- Single transducer rig (soundcard, microphone, speaker)
- GNU Radio, TensorFlow, Natural Language Toolkit
- Classes are English phonemes (e.g. sss, vvv)
- Listen as computers discover communication

2018 Deepmod: Powerline Communications (PLC) Channel





PLC channel: Use existing (and unintended) infrastructure to transmit information. Can be used in home networks or disaster scenarios.

PLC Deepmod: Swap out speaker/microphone for powerline couplers. Same machine.

Deepmod learns to communicate.

2018 Deepmod: RF (Wireless) Channel

Radio Frequency (RF) channel: Is the *de facto* channel for "last mile" communications. Transducers in this case are antennas.

RF Deepmod

- Sample rate = 1 Msps
- Center frequency = 900 MHz
- SNR adjusted to match simulation
- 256 classes, 16 (real) samples, **1 bit per sample**
- **0 signal processing blocks**
- High rate communications

Deepmod learns to communicate.

Don't Ask:

Q1: What does the deepmod constellation look like?
A1: There's no constellation.

Q2: What equalizer does deepmod use?
A2: There's no equalizer.

Q3: How does deepmod handle CFO correction?
A3: It just does. Deal with it.

Q4: How does it perform against the equivalent human system?
A4: I can't win this argument…

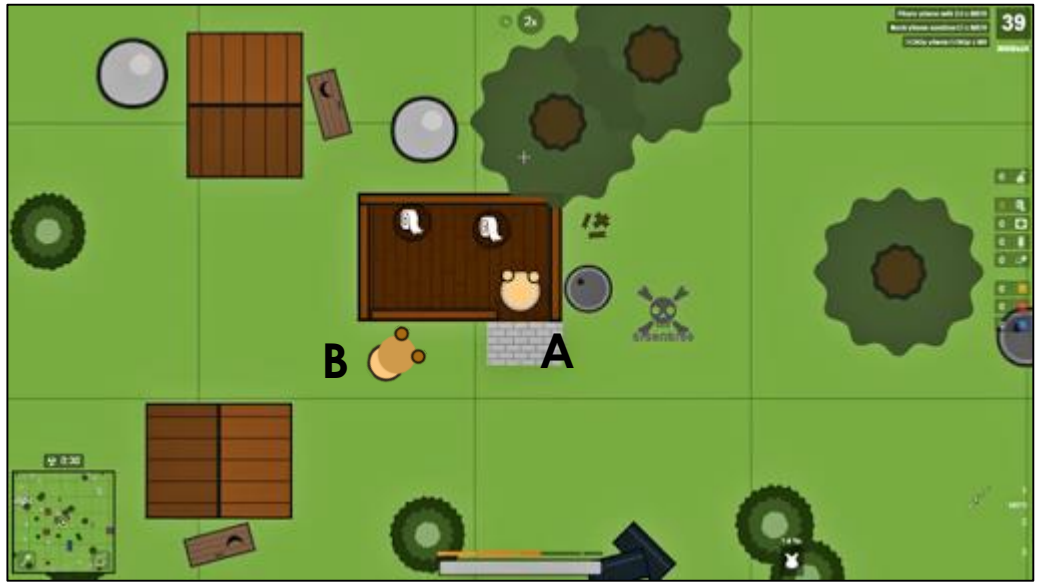
- If deepmod does worse in simulation people will say "Ha! BPSK in AWGN is 1 dB better!"
- If deepmod is better over-the-air people will say: "Ha! You just need to extend your equalizer! Lower beta! Change modulation! Use an FEC! Etc.! Etc.!"

Do Ask:

But is deepmod intelligent?

The Turing Test

"…a test of a machine's ability to exhibit intelligent behavior equivalent to, or indistinguishable from, that of a human"



The Imitation Game

Toon A wants to find out if Toon B is a bot.

Toon A: "Hey you want to team up?"
Toon B: "Sure just come out of that house and we'll own some stuff!"

Is Toon B a bot or human?

1. The primary difficulty of the Turing Test is knowing what questions to ask.

2. The secondary difficulty is knowing how to interpret the answers given.

The CAPTCHA Test

Completely Automated Public Turing test to tell Computers and Humans Apart

A counterpart to the Turing Test. Now a computer is determining if YOU are intelligent.

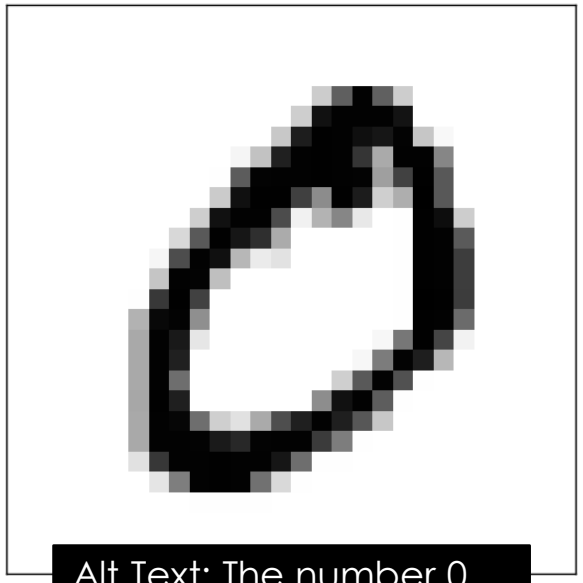
The Dr. Anderson Test

Common Student Question:

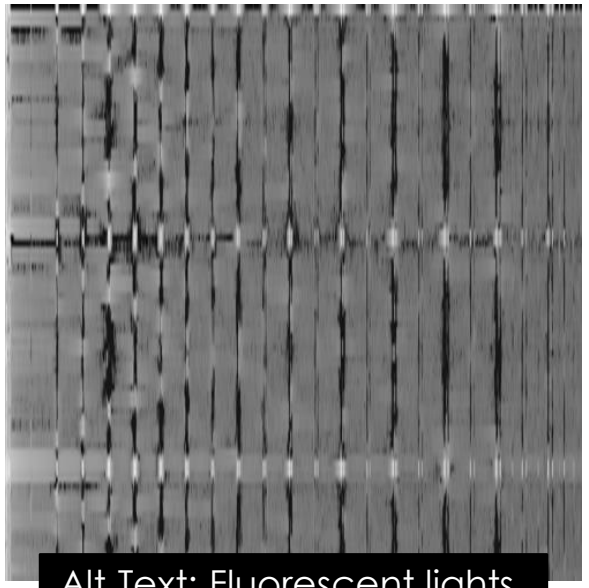
"Dr. Anderson, do you think I could code this up to automatically classify [whatever]?"

Common Teacher Response:

"Well, can *you* classify it?"



Alt Text: The number 0



Alt Text: Fluorescent lights

Alt Text: A girl on a swing

Any cognitive ability achievable by humans can ultimately be achieved by a machine

Radio Intelligence Test

Turing:	A human guessing if a computer is a human or not
CAPTCHA:	A computer guessing if a human is a computer or not
Anderson:	If a human can guess it then so can a computer

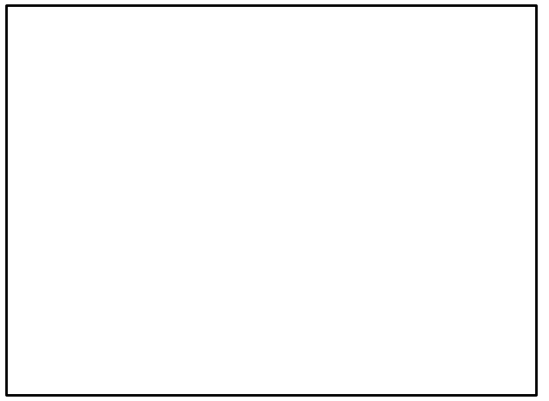
An observation: Artificial radio intelligence may be easier to test than artificial human intelligence. We don't care how the machine answers the question; we just care if the answer is correct.

For now, let's just say: A radio system designed artificially by a computer is deemed intelligent if a human - given an unlimited amount of time - would derive a system with similar behavior for: hardware, environment, and objectives given.

Man vs. Demon

Man vs. Demon

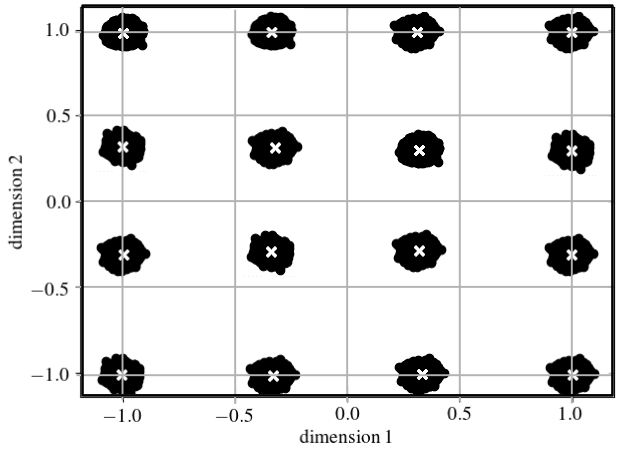
- This is a noisy symbol  representing four bits (e.g. 1101)
- We want to place 16 of these on a fenced, flat space so that no two clusters overlap (overlap means bit errors!)
- Minimize the bit-error rate



Man vs. Demon

- This is a noisy symbol  representing four bits (e.g. 1101)
- We want to place 16 of these on a fenced, flat space so that no two clusters overlap (overlap means bit errors!)
- Minimize the bit-error rate

Human Invented 16-QAM

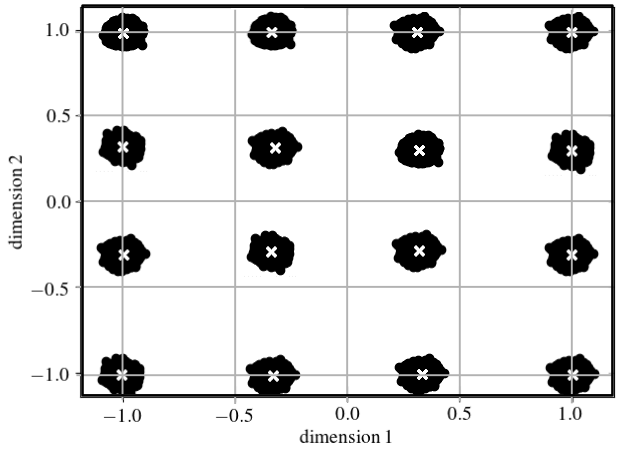


- This is a noisy symbol  representing four bits (e.g. 1101)
- Give a machine a convolutional neural network with two dimensional fully-connected inner layer

Man vs. Demon

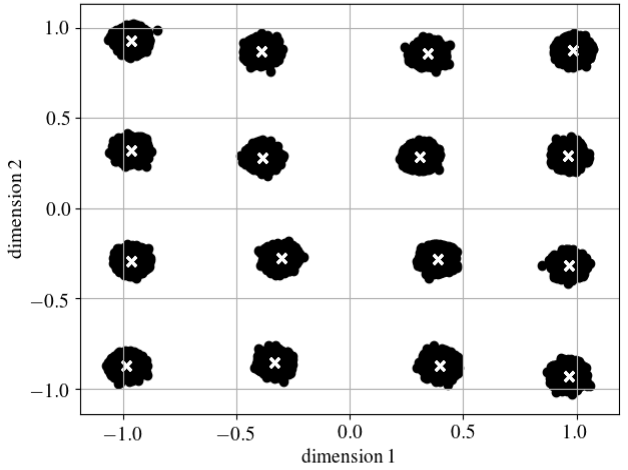
- This is a noisy symbol  representing four bits (e.g. 1101)
- We want to place 16 of these on a fenced, flat space so that no two clusters overlap (overlap means bit errors!)
- Minimize the bit-error rate

Human Invented 16-QAM



- This is a noisy symbol  representing four bits (e.g. 1101)
- Give a machine a convolutional neural network with two dimensional fully-connected inner layer

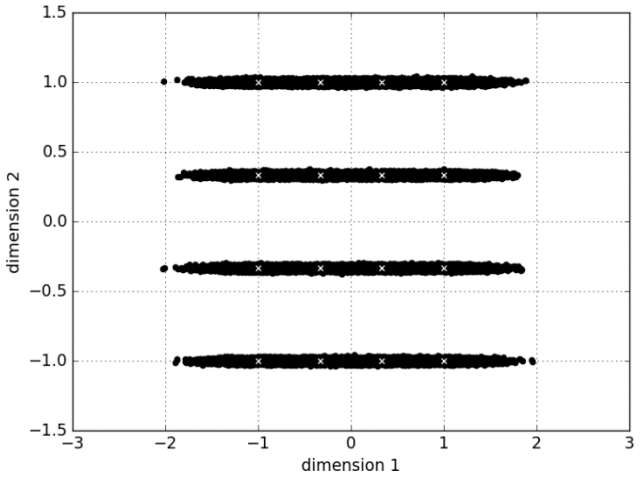
Machine Invented 16-QAM



Man vs. Demon: A New Environment

- Most channels don't have "nice" noise…
- This is now a noisy symbol  representing four bits (e.g. 1101)
- The human-invented 16-QAM is terrible with massive cluster overlaps (bit errors)
- What can we do?

Human Invented 16-QAM



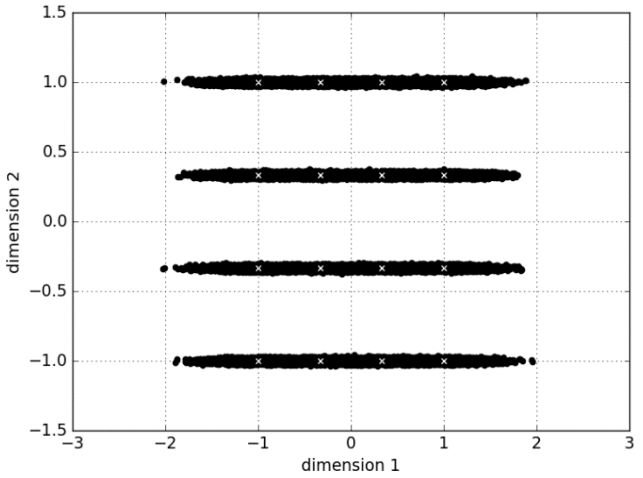
Man vs. Demon: A New Environment

- Most channels don't have "nice" noise…
- This is now a noisy symbol  representing four bits (e.g. 1101)
- The human-invented 16-QAM is terrible with massive cluster overlaps (bit errors)
- What can we do?

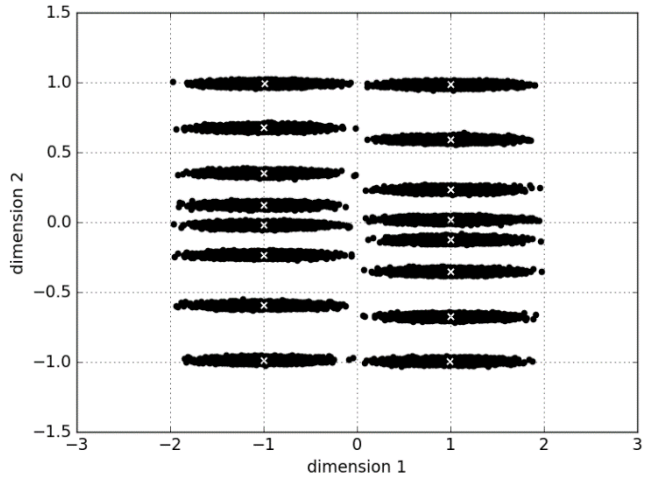
- Same machine. New discovery.

IMPORTANT If the human radio could change modulation from 16-QAM to BPSK then that's **adaptation**. Inventing 8x2-QAM *in situ* is **intelligence**.

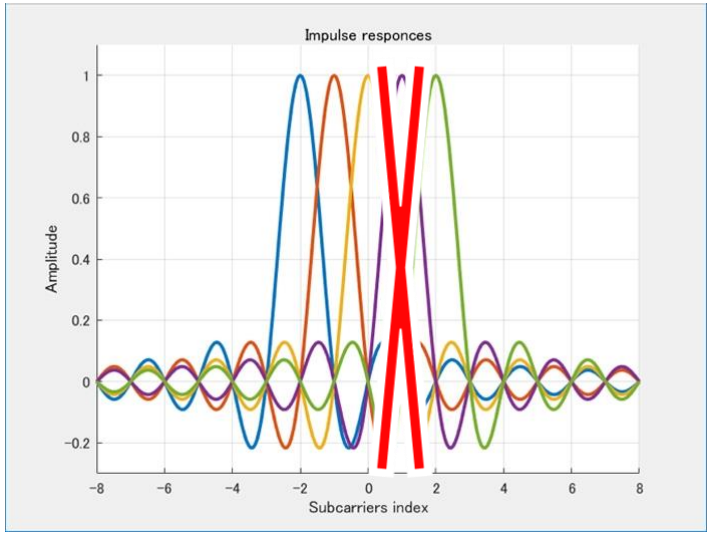
Human Invented 16-QAM

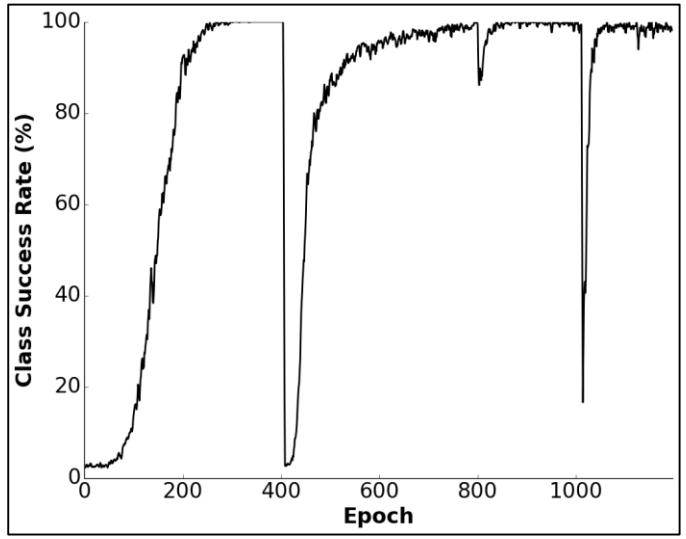


Machine Discovered 8x2-QAM



Test 1: Contested Channel





Test 1: Place the radio into an environment with narrowband interference

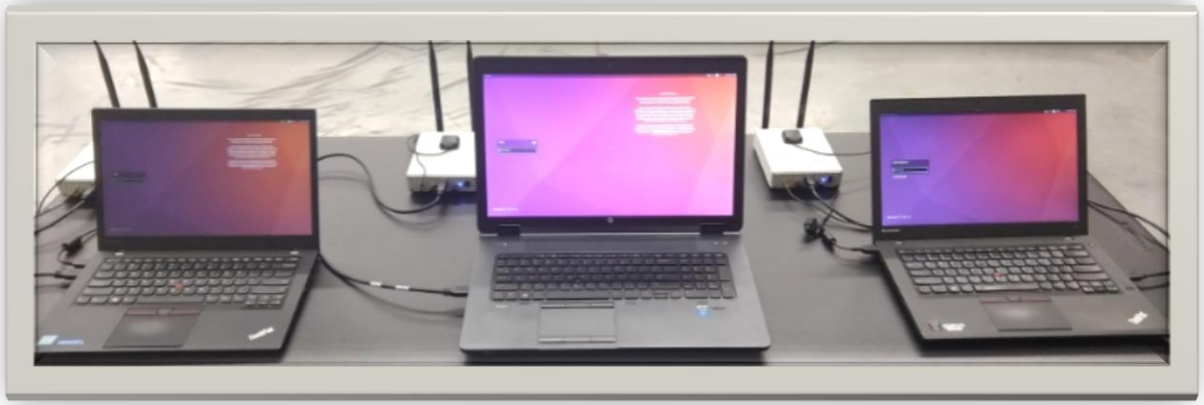
What A Human Might Do

- Notch filter on frontend would remove interference but may also harm narrowband signals.
- With OFDM you could suppress the affected subcarrier.
- Specific equalizer maybe?

What Deepmod Did

- First learns to communicate without interference present
- Goes dumb with jammer turned on
- Continued learning; reestablishes a comms link in the presence of the interference.
- CNN helped maybe?

Test 2: Relay Channel



Test 2: Place the radios into an environment with a single-hop amplify-and-forward relay channel

What A Human Might Do

- Relay channel may result in heterogenous links
- Adapt power and/or coding depending on direction and channel quality
- Additional filtering for CFO / phase effects

What Deepmod Did

- A third node used as relay (just a dumb AFR node)
- No direct communications between deepmod nodes
- Deepmod learns to communication at the effective SNR level

Test 3: Lone Survivor Channel

Test 3: Place multiple single antenna radios into the same environment with the same objective

Deepmod0

Deepmod1

Deepmod0

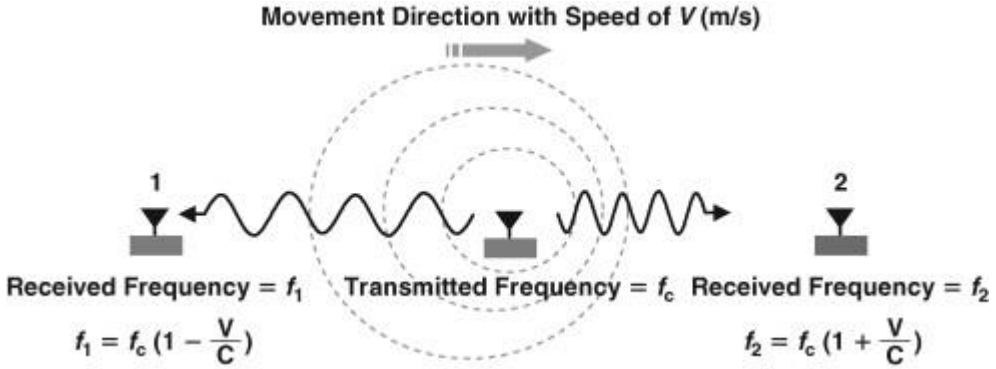
What A Human Might Do

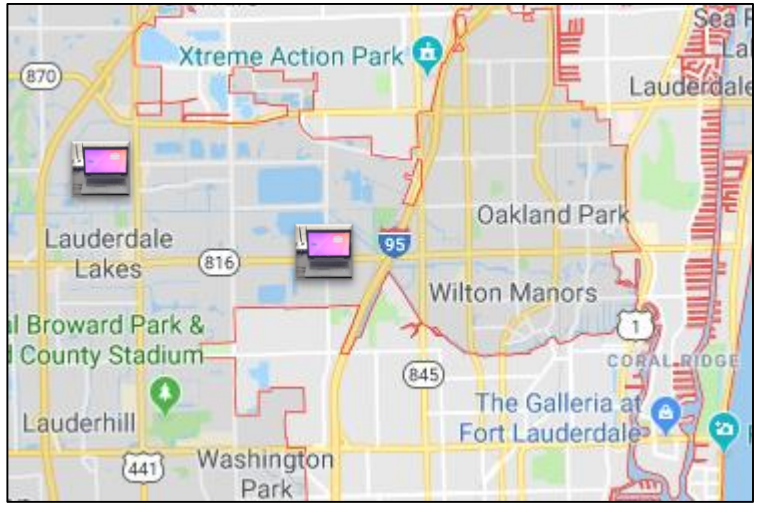
- Cooperative MIMO channel
- Share channel state information between all transmitting nodes and receiver
- Fine-grained synchronization
- Have signals combine constructively OTA

What Deepmod Did

- Two deepmod nodes are assigned "deepmod0" the other node is "deepmod1"
- Not aware of other deepmod0
- The two node zeros initially treat each the node as environment noise
- Eventually cooperated for "3 dB" gain

Test 4: Mobile Channel





Test 4: Allow one radio to move

What A Human Might Do

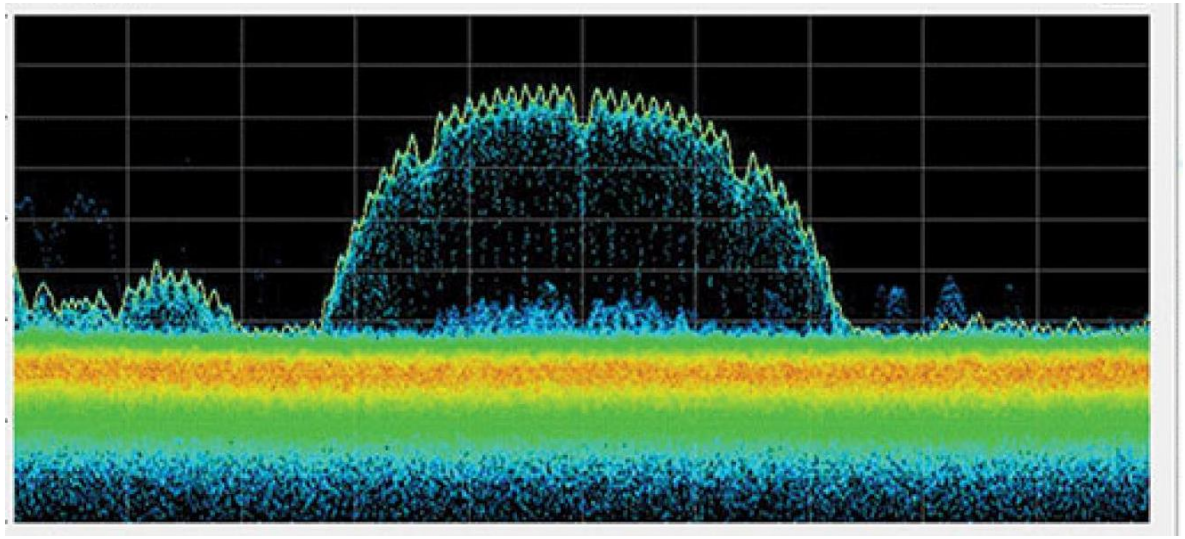
- Mobility affects channel coherence time and fading
- Train during preamble and equalize at receiver?
- Space-time block coding
- Estimate Doppler spreading and then compensate

What Deepmod Did

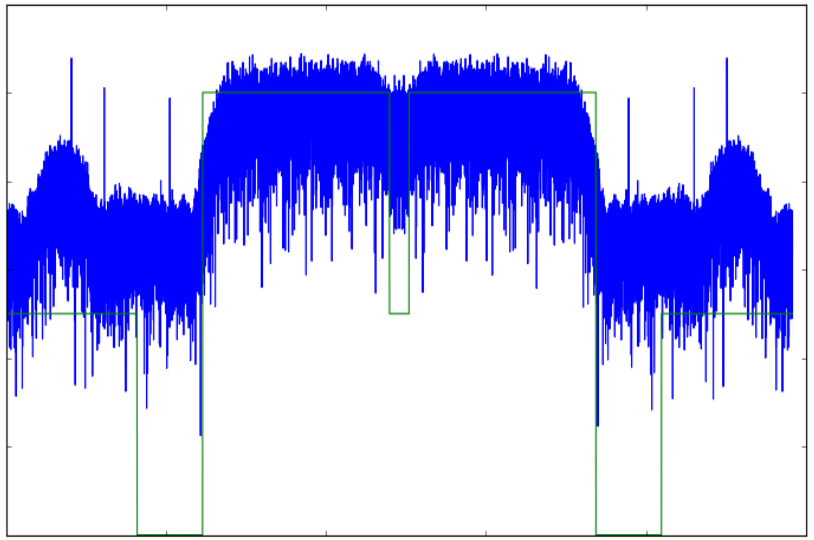
- Deepmod0 placed in hotel room; deepmod1 placed in back of vehicle
- Nodes learn to communicate while stationary
- Similar behavior to NB jammer during movement
- Training epochs affected by velocity

Test 5: Narrowband

Google image search:
"narrowband spectral envelope"…



… and then tell deepmod to try and look like it.



Test 5: Require spectrum to be narrowband.

What A Human Might Do

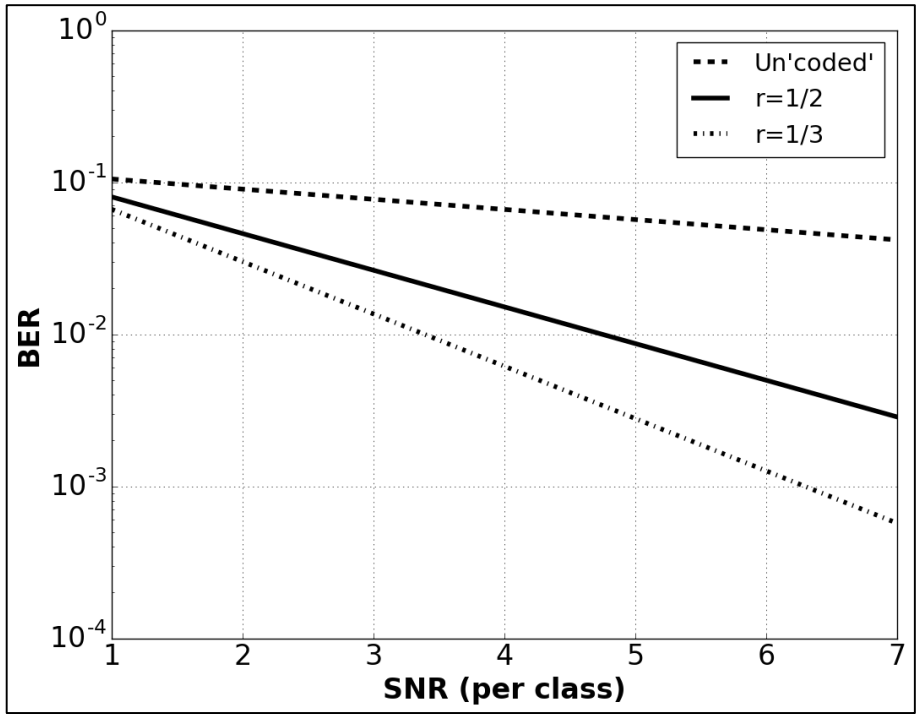
- Results naturally from whatever modulation is being used
- If artificial, pulse shape the entire packet to match envelope
- Add artificial noise to missing bands

What Deepmod Did

- Keep objective of "try and minimize bit (class) error rate"
- Also give objective of "look like these points in the spectrum"
- Deepmod converges to communications while evolving to narrowband spectrum

Test 6: Spectral Efficiency

Test 6: Give radios *r* less spectral efficiency (or 1/*r* more samples per class).



What A Human Might Do

- Higher energy per bit
- Repetition code
- Block code
- Turbo code
- ACK / Retransmission

What Deepmod Did

- I don't know…
- Rate less than one means more samples per class?
- Increase innermost "hidden layer"
- Was able to lower the effective BER for the same power per class (bit)
- Shannon and Turing walk into a bar…

Conclusion

- Future bands of spectrum will require some degree of intelligence from wireless devices – at all layers of the protocol stack – before transmission is allowed
- A "Turing Test" for radios is needed to determine sufficient intelligence
- It's the communities' (our) responsibility to 1) Determine which intelligence the PHY layer is responsible for
- And 2) Define a set of "questions" to "ask" the radio to determine intelligence:
  - How do you react to a relay channel?
  - How do you react to multiple objectives?
  - How do you react to mobility?
  - How do you react to cooperation?
  - How do you react to statistical channel changes?
  - How do you react to spectral efficiency?
  - How do you react to nonideal environments?
  - Etc.
- And 3) Determine the appropriate radio "responses" that imply intelligence:
  - I mitigated the jammer.
  - I decreased my error floor.
  - I narrowed my spectral use.
  - Etc.
- Intelligent? Yes/No!

Questions?