Bits over the Air: Exploring Wireless Systems

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The goal of this research project:

We will build a working wireless communication system from scratch!

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Bits over the Air

- We will use acoustic instead of radio waves
- Acoustic waves have the same behavior as radio waves, but we can sense them (with our ears!)

- Everything you will learn directly applies to wireless communication with radio waves!

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Wireless communication is everywhere!

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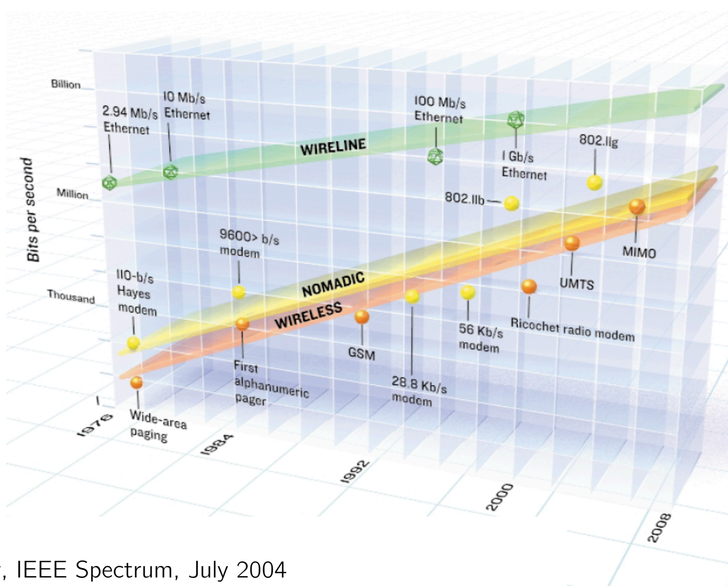
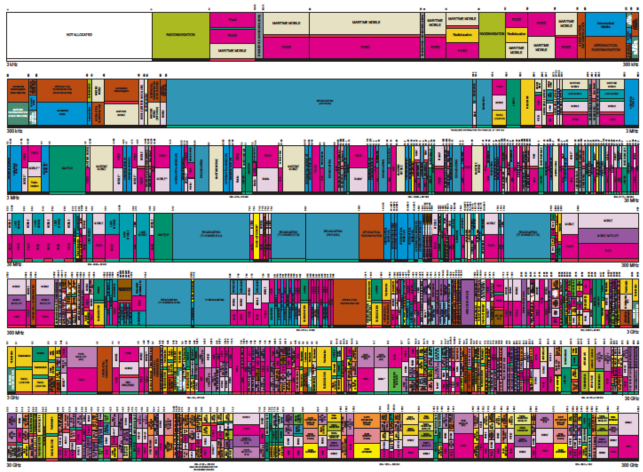
Data rates double every 18 months!



Cherry, IEEE Spectrum, July 2004

The wireless spectrum is crowded!



2011 US frequency allocation chart

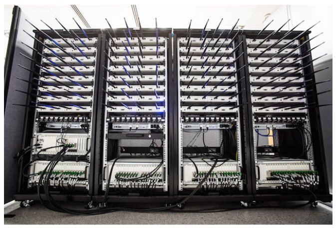
Wireless spectrum is expensive!

- Germany: UMTS, $57B
- UK: 3G, $43B
- US: 700MHz band, $19B

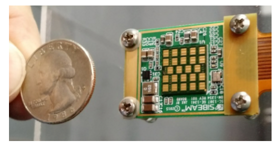
- Cost of One World Trade Center: USD 3.9B

We need new technologies!

- 5^{th} generation (5G) wireless systems will use



massive MIMO



millimeter-wave communication

…but what about 6G?


Donald J. Trump

Follow

I want 5G, and even 6G, technology in the United States as soon as possible. It is far more powerful, faster, and smarter than the current standard. American companies must step up their efforts, or get left behind. There is no reason that we should be lagging behind on.........

Large and active research community…

IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS

IEEE TRANSACTIONS ON INFORMATION THEORY

IEEE Communications MAGAZINE

IEEE 2015 GLOBECOM GLOBAL COMMUNICATIONS CONFERENCE EXHIBITION & INDUSTRY FORUM 6-10 DECEMBER 2015 // SAN DIEGO, CA, USA CONNECTING ALL THROUGH COMMUNICATIONS

IEEE TRANSACTIONS ON COMMUNICATIONS

ISIT HONG KONG 2015

IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS

IEEE ICC IEEE International Conference on Communications

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and..... Jobs!

Qualcomm · Google · facebook · Samsung · Broadcom · Ericsson · Northrop Grumman · intel · Raytheon · Nokia Bell Labs · MITRE · XILINX

- And many, many more with a degree in Electrical and Computer Engineering...!

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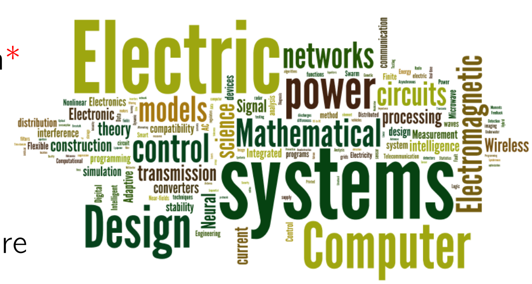
Wireless comm. is interdisciplinary!

- Combines a large number of disciplines from ECE
  - Programming*
  - Statistics* and Math*
  - Signal processing*
  - Algorithm design*
  - Information theory
  - Computer architecture
  - Circuits and systems
  - Electromagnetic waves* and physics



*This research project will touch on these!

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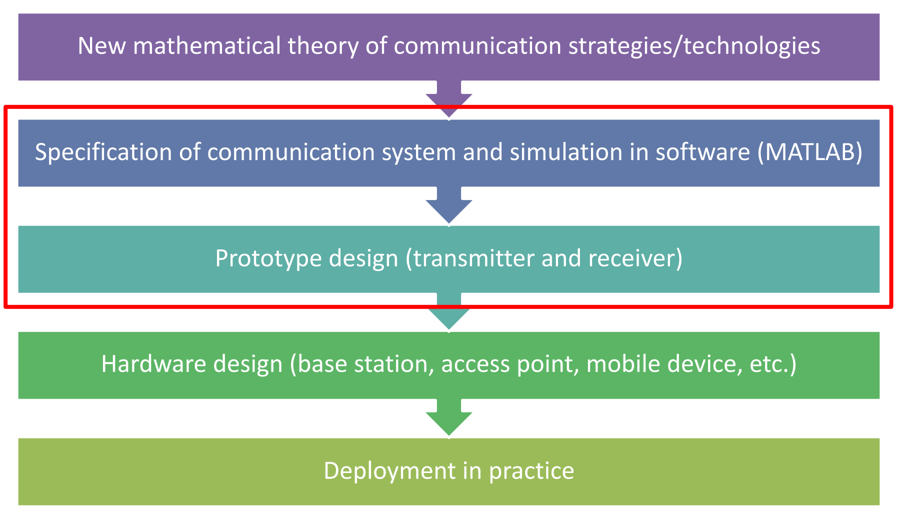
Project overview

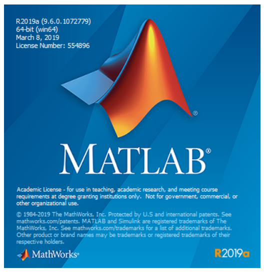
Bits over the Air

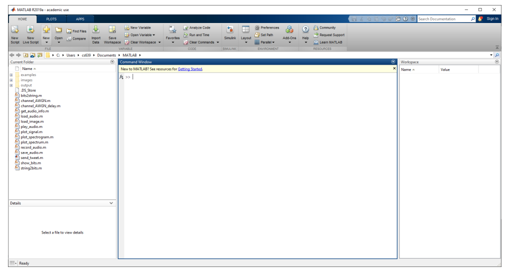
How are comm. systems designed?



Simplified!

MATLAB programming





- The standard software for scientific computing in academia as well as industry
- Used in engineering (not only ECE!), computer science, math, physics, etc.

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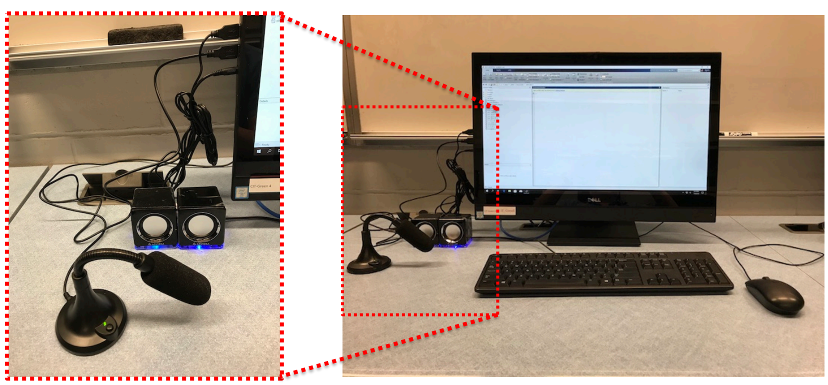
Audio signal processing



- Loudspeakers are used as transmit antenna
- USB microphone used as receive antenna

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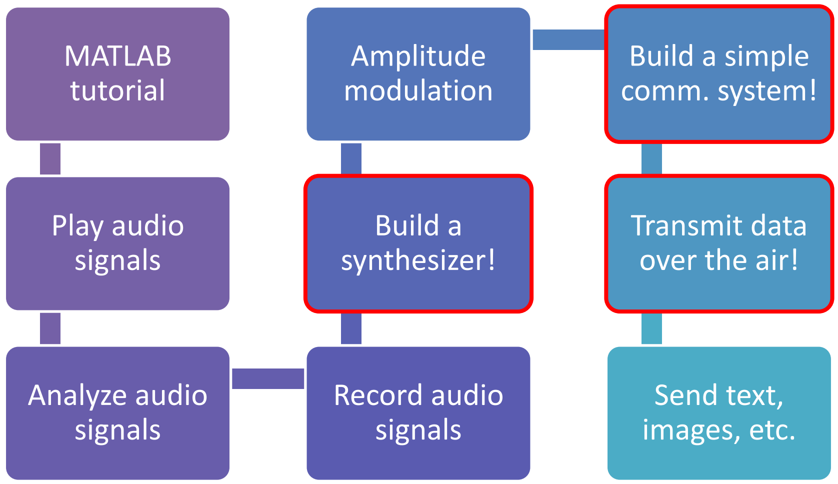
Basic flow of labs



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Project organization

- Daily pre-labs (30-40min) in Phillips 219
  - Introduce key concepts
  - Explain next steps and outline daily goals
- Small groups (2-3 students) work in ACCEL lab with MATLAB and audio hardware
- Labs are divided into 10 modules
  - Consist of tutorials, explanations, and activities
  - Enables groups to progress at their own pace

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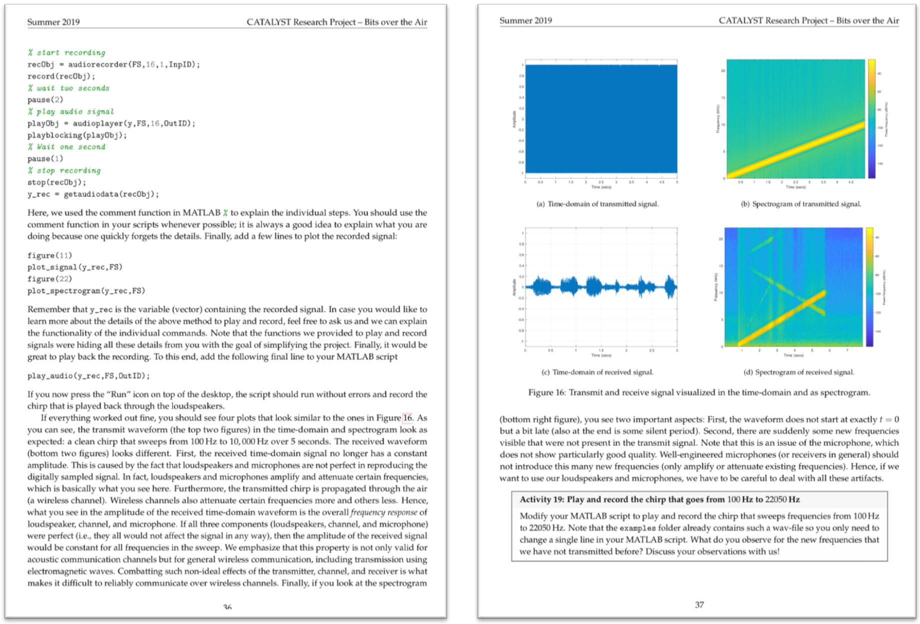

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```
% start recording
recObj = audiorecorder(FS,16,1,InpID);
record(recObj);
% wait two seconds
pause(2)
% play audio signal
playObj = audioplayer(y,FS,16,OutID);
playblocking(playObj);
% Wait one second
pause(1)
% stop recording
stop(recObj);
y_rec = getaudiodata(recObj);
```

Here, we used the comment function in MATLAB % to explain the individual steps. You should use the comment function in your scripts whenever possible; it is always a good idea to explain what you are doing because one quickly forgets the details. Finally, add a few lines to plot the recorded signal:

```
figure(11)
plot_signal(y_rec,FS)
figure(22)
plot_spectrogram(y_rec,FS)
```

Remember that y_rec is the variable (vector) containing the recorded signal. In case you would like to learn more about the details of the above method to play and record, feel free to ask us and we can explain the functionality of the individual commands. Note that the functions we provided to play and record signals were hiding all these details from you with the goal of simplifying the project. Finally, it would be great to play back the recording. To this end, add the following final line to your MATLAB script

```
play_audio(y_rec,FS,OutID);
```

If you now press the "Run" icon on top of the desktop, the script should run without errors and record the chirp that is played back through the loudspeakers.

If everything worked out fine, you should see four plots that look similar to the ones in Figure 16. As you can see, the transmit waveform (the top two figures) in the time-domain and spectrogram look as expected: a clean chirp that sweeps from 100 Hz to 10,000 Hz over 5 seconds. The received waveform (bottom two figures) looks different. First, the received time-domain signal no longer has a constant amplitude. This is caused by the fact that loudspeakers and microphones are not perfect in reproducing the digitally sampled signal. In fact, loudspeakers and microphones amplify and attenuate certain frequencies, which is basically what you see here. Furthermore, the transmitted chirp is propagated through the air (a wireless channel). Wireless channels also attenuate certain frequencies more and others less. Hence, what you see in the amplitude of the received time-domain waveform is the overall *frequency response* of loudspeaker, channel, and microphone. If all three components (loudspeakers, channel, and microphone) were perfect (i.e., they all would not affect the signal in any way), then the amplitude of the received signal would be constant for all frequencies in the sweep. We emphasize that this property is not only valid for acoustic communication channels but for general wireless communication, including transmission using electromagnetic waves. Combatting such non-ideal effects of the transmitter, channel, and receiver is what makes it difficult to reliably communicate over wireless channels. Finally, if you look at the spectrogram

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(a) Time-domain of transmitted signal. (b) Spectrogram of transmitted signal.

(c) Time-domain of received signal. (d) Spectrogram of received signal.

Figure 16: Transmit and receive signal visualized in the time-domain and as spectrogram.

(bottom right figure), you see two important aspects: First, the waveform does not start at exactly $t = 0$ but a bit late (also at the end is some silent period). Second, there are suddenly some new frequencies visible that were not present in the transmit signal. Note that this is an issue of the microphone, which does not show particularly good quality. Well-engineered microphones (or receivers in general) should not introduce this many new frequencies (only amplify or attenuate existing frequencies). Hence, if we want to use our loudspeakers and microphones, we have to be careful to deal with all these artifacts.

Activity 19: Play and record the chirp that goes from 100 Hz to 22050 Hz

Modify your MATLAB script to play and record the chirp that sweeps frequencies from 100 Hz to 22050 Hz. Note that the examples folder already contains such a wav-file so you only need to change a single line in your MATLAB script. What do you observe for the new frequencies that we have not transmitted before? Discuss your observations with us!

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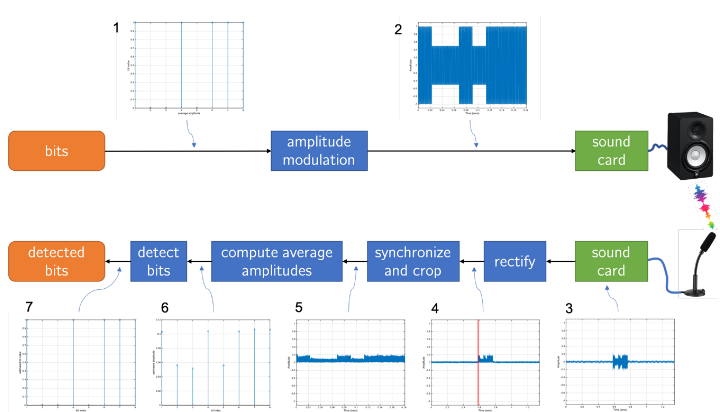
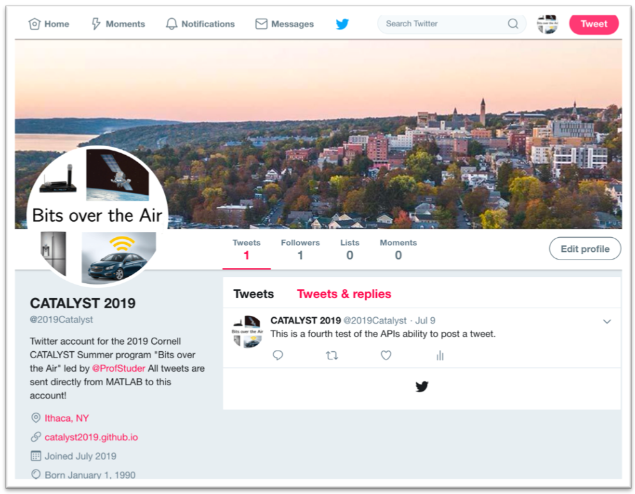
Taken from Module 5: Record Audio Signals in MATLAB

Final communication system



- Reliably achieves more than 200 bit per second over 0.5m without special tricks
- Can transmit raw bits, text, images, and…

…tweets directly from MATLAB!



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Project schedule

	Monday	Tuesday	Wednesday	Thursday	Friday
1pm-2pm	Pre-Lab 1: Introduction to MATLAB and digital communication	Pre-Lab 2: Signal processing, time-domain, spectrum, and spectrogram	Pre-Lab 3: Generating music with MATLAB and communication system basics	Pre-Lab 4: Communication via amplitude modulation and synchronization	Pre-Lab 5: Bits over the air: transmitting text and images over the air (reliably!)
2pm-3pm	Module 1: MATLAB basics 1	Complete previous modules	Complete previous modules	Complete previous modules	Complete previous modules
	15min break	15min break	15min break	15min break	15min break
3pm-4pm	Module 2: MATLAB basics 2	Module 4: Spectrum and spectrogram	Module 6: Generating music in MATLAB	Module 8: Simple communication system 2	Module 10: Transmitting bits over the air
4pm-5pm	Module 3: Play audio in MATLAB	Module 5: Record audio in MATLAB	Module 7: Simple communication system 1	Module 9: Synchronization	Work on presentations

- Presentations: Saturday 9:30am to 11:30am

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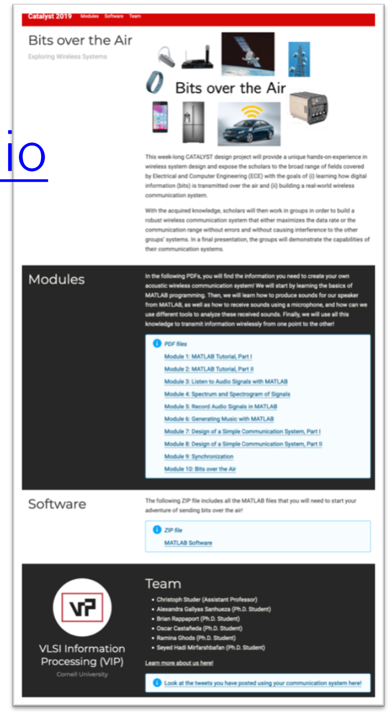
Project website:
catalyst2019.github.io

- Basic information
- Module handouts for download
- MATLAB functions and example files for download



Enjoy your week at Cornell!

…any questions?

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