Digital Wireless Communication: Physical Layer Exploitation

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Wireless is Everywhere

- Cellular networks
- Local area networks
- Personal area networks
- Emerging applications
Where is Wireless Taught?

Undergraduate
- Signals and Systems
- Digital Signal Processing
- Analog Communication
- Digital Communication

Graduate
- Intro to Wireless
- Advanced Wireless

a typical curriculum (many exceptions of course)
Why at the Graduate Level?

- It involves many different areas of expertise
  - Digital communication
  - Propagation
  - Antennas
  - Signal Processing
  - Probability
  - Etc.

- Hot area of research
  - Requires some depth in areas of expertise

- Curriculum is not widely available (vs e.g. signals and systems)
Where Could it be Taught?

Undergraduate

Signals and Systems
Digital Signal Processing
Wireless Digital Comm.

Graduate

Digital Communication
Advanced Wireless

Lab-based approach to teach wireless to undergraduates
Wireless Communications Lab @ UT

Premises of the course

- Wireless communication can be taught to undergraduates
- Wireless communication can be taught without a communication background
- Students can implement what they learn while they learn it

Key ideas

- Teach digital communication from a digital signal processing perspective
- Incorporate modulation, channel estimation, equalization, synchronization
- Use algorithmic design examples, not comprehensive theory
- Leverage flexible software defined radio prototyping
- Exploit LabVIEW & USRP

Developed and tested over 7 years
DSP Approach to Wireless

Use systems approach for communication
How this Fits with the Lab

transmitter

Source → Channel Coding → Modulation → D/A → RF Upconversion

receiver

Sink ← Channel Decoding ← Demodulation ← A/D ← RF Downconversion

Real world

channel

Laptop with LabVIEW
(all digital signal processing)

NI USRP 2921

Real world

channel

Laptop with LabVIEW
(all digital signal processing)
How it Works at UT

- The course is cross-listed for undergrads and grads
  - Pre-requisites: a course in digital signal processing and a course on probability
  - Undergraduates take in 3rd or 4th year as a 4 credit course
  - Graduate students take their 1st or 3rd semester

- Structure of the course
  - 3 hours of lecture per week, covers the theory of the course
  - 3 hours in the lab per week, demonstrate what has been learned
  - Homework assignments test the theory
  - Prelabs, labs, lab reports test what has been learned in the lab
  - Yes there are exams too.....(why do the students complain of high workload??)
Content of the Course

- Digital comm overview
- Signals, stochastic processes
- Transforms, sampling theorem
- Frequency response, power spectrum, bandwidth
- Upconversion, downconversion, complex baseband
- Quadrature pulse amplitude modulation
- Optimal pulse shapes
- Maximum likelihood detection in AWGN
- Sample timing offset, sample timing algorithms
- Frequency selective channels, least squares channel estimation
- Frequency offset estimation and correction, frequency domain equalization
- Single carrier frequency domain equalization, OFDM, the cyclic prefix
- IEEE 802.11a, GSM standard
- Introduction to propagation, large-scale fading, link budgets, path-loss
- Small-scale fading, coherence time, coherence bandwidth
- Probability of error in fading channels
- Sources of diversity, Alamouti space-time code, maximum ratio combining
- Introduction to MIMO communication, spatial multiplexing
- Introduction to MIMO-OFDM, highlights of the IEEE 802.11n standard

Mathematical preliminaries

Basic digital comm

Channel impairments

Standards

Fading

MIMO
Content of the Course

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Done in the Lab
Materials Developed for Lecture

- **Textbook that describes the theory**
  - Book is 200 pages, unpublished but available for use for free (has been used as is for several years)
  - Target completion date is end of 2012

- **Lecture notes**
  - In LaTeX form approximately 84 pages
  - Slides are forthcoming

Implementing pulse-shaping at the receiver

- **Objective:** Implement discrete-time pulse shaping at the receiver using oversampling combined with downsampling.
- **Objective:** Apply downsampling identities to implement and simplify receive pulse shaping.
- Thus far we have considered the following QAM receiver:

  - This structure does not map to a flexible implementation
    - Requires analog matched filtering
    - Take advantage of flexible digital processing
    - Does not lend itself to various synchronization tasks
  - How can we implement pulse-shaping in discrete-time?
Materials Developed for Lab

- Laboratory manual
  - DIGITAL COMMUNICATIONS: Physical Layer Exploration Using the NI USRP
  - 141 pages
  - 8 Laboratory experiments
- Lab experiments
  - Background information
  - Include prelab to be completed prior to lab
  - Laboratory experiments
  - Postlab
- Complete software framework
- TA guide with solutions

Included with the Digital Communications Teaching Bundle

Outline of Lab Manual

Preface vii

About the Author xi

Lab 1: Part 1 Introduction to NI LabVIEW 1
Lab 1: Part 2 Introduction to NI RF Hardware 10
Lab 2: Part 1 Modulation and Detection 22
Lab 2: Part 2 Pulse Shaping and Matched Filtering 35
Lab 3: Synchronization 51
Lab 4: Channel Estimation & Equalization 63
Lab 5: Frame Detection & Frequency Offset Correction 82
Lab 6: OFDM Modulation & Frequency Domain Equalization 99
Lab 7: Synchronization in OFDM Systems 115
Lab 8: Channel Coding in OFDM Systems 130
Appendix A: Reference for Common LabVIEW VIs 139

Bibliography 141
Lab 3: Synchronization:
Symbol Timing Recovery in Narrowband Channels

Summary

In this lab you will consider the problem of symbol timing recovery also known as symbol synchronization. Timing recovery is one of several synchronization tasks; others will be considered in future labs.

The wireless communication channel is not well modeled by simple additive white Gaussian noise. A more realistic channel model also includes attenuation, phase shifts, and propagation delays. Perhaps the simplest channel model is known as the frequency flat channel. The frequency flat channel creates the received signal

\[ z(t) = \alpha e^{j\phi} x(t - \tau_d) + v(t), \]

where \( \alpha \) is an attenuation, \( \phi \) is a phase shift, and \( \tau_d \) is the delay.

The objective of this lab is to correct for the delay caused by \( \tau_d \) in discrete-time. The approach will be to determine an amount of delay \( \hat{k} \) and then to delay the filtered received signal by \( \hat{k} \) prior to downsampling. This will modified the receiver processing as illustrated in Figure 1.

Two algorithms will be implemented for symbol synchronization in this lab: the maximum energy method and the Early Late gate algorithm. The maximum energy method attempts to find the sample point that maximizes the average received energy. The early–late gate algorithm implements a discrete-time version of a continuous-time optimization to maximize a certain

![Figure 1](image.png)

Figure 1: Receiver with symbol synchronization after the digital matched filtering.
Methodology for the Lab

- All labs have already been implemented, functions are locked
  - Both over-the-air and simulation capable functions
- Students work in groups of 2 or 3
- Each week students implement a new block
  - For example modulation, or demodulation, or some synchronization
- During the pre-lab
  - Student implements software, verifies it is correct, answers prelab questions
- During the lab
  - Student demonstrates correction function to TA, answers inlab questions
- After the lab
  - Students write a short lab report documenting what they learned
Lab Size and Equipment

- Course has 30-40 students enrolled every year
  - Half undergraduates, half graduates

- Lab has ten workstations for transmit / receive
  - Students work in teams of 2 or 3
  - Accommodate 20 students in the lab for 3 hours
  - One TA services two lab sessions, grades homework, holds office hours
Operational Challenges

- Covering material required before the lab
  - Only an issue the first few weeks of the class

- Keeping PCs up-to-date
  - Solved by requiring students to use their own laptops

- Finding high quality TAs with enough experience
  - Not an issue after a couple of years

- Avoiding copying of code, plagiarism
  - Need better tools for detecting plagiarism in graphical code

- Helping students that fall behind
  - The labs build on each other every week
  - Falling behind can be a big problem
Possible Evolution of the Lab

- Lab equipment can be checked out, experiments performed
  - How to avoid all students doing the same thing?
  - Do they really do the experiment themselves?

- Lab equipment can be networked and accessed remotely
  - How to manage access to the equipment?
  - How to configure equipment for experiments?
  - What is the difference between this and simulation?

- Lab equipment in the cloud
  - Perhaps not owned by the university, equipment pooled together
  - Some examples of this already for research applications
  - Is it still “real”??
Conclusion

- Wireless communication can be taught to undergraduates

- Laboratory approach makes wireless more concrete
  - Avoids simply drowning in mathematics
  - Useful for graduate students as well

- Students build a practical foundation for further study
  - Good preparation for industry
  - Practical insights make for more relevant research
Questions?