MAS.S61: Emerging Wireless & Mobile Technologies
aka The “Extreme IoT” Class

Lecture 3:
Fundamentals of Wireless Sensing & Localization (Con’t)
Fundamentals of Communications & Connectivity

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Logistics & Norm Settings

• What to do now?
  1. Turn on your video (if your connection allows it)
  2. Mute your mic (unless you are the active speaker)
  3. Open the “Participant” List
     • Make sure your full name is shown

• If you have a question:
  - Use the chat feature to either write the question or to indicate your interest in asking the question
  - We will be monitoring the chat
  - Unmute -> ask question -> mute again
  - Once done asking/answering, please state “Done” to clearly mark it (helps translation/moderation)
  - Same procedure for answering questions

• This lecture will be recorded. It will only be accessible to people in the class
Objectives of Today’s Lecture

1. Learning the fundamentals of wireless (aka WiFi) sensing and its current industry trends
2. Learning the fundamentals of end-to-end wireless communications:
   • The physical, mathematical, engineering, and design fundamentals
   • “Why are these systems designed the way they are”
   • Case study of a new wireless communication system (underwater-to-air comms)
Recap: Localization Approaches

1. Identify-based
2. RSSI-based (including fingerprinting)
3. Phase-based
4. AoA+Triangulation
5. ToF+Trilateration
6. DTOA
Wireless Sensing from Reflections

Operates through occlusions
Measuring Distances

Distance = Reflection time \times \text{speed of light}
Measuring Reflection Time

Option 1: Transmit short pulse and listen for echo

![Graph showing Tx pulse and Rx pulse with Reflection Time indicated.](#)
Measuring Reflection Time

**Option 1:** Transmit short pulse and listen for echo

Capturing the pulse needs sub-nanosecond sampling

Why?

Would it also be a problem for acoustic or ultrasound-based methods?
FMCW: Measure time by measuring frequency

How does it look in time domain?
FMCW: Measure time by measuring frequency

How do we measure $\Delta F$?

Reflection Time

$$Reflection\ Time = \frac{\Delta F}{slope}$$
Measuring $\Delta F$

- Subtracting frequencies is easy (e.g., removing carrier in WiFi)
- Done using a mixer (low-power; cheap)

Signal whose frequency is $\Delta F$

let’s talk about FFTs a bit — freq
Basics of Fourier Transform
Measuring $\Delta F$

- Subtracting frequencies is easy (e.g., removing carrier in WiFi)
- Done using a mixer (low-power; cheap)

Signal whose frequency is $\Delta F$

$\Delta F \rightarrow$ Reflection Time $\rightarrow$ Distance
Mapping Distance to Location

Person can be anywhere on an ellipse whose foci are \((Tx, Rx)\)

By adding another antenna and intersecting the ellipses, we can localize the person.
Implementation

• Built FMCW front-end
  – Connected to USRP

• Band: 5.5-7.2 GHz

• Transmit 70 $\mu$W
  – 1000x lower power than WiFi Access Point
Ground Truth via VICON

- VICON uses an array of infrared cameras on the ceiling and operates in line-of-sight
  - It achieves sub-cm-scale accuracy
- Our device is placed outside the room
Through-Wall Localization Accuracy

100 experiments: ½ million location measurements

Centimeter-scale localization without requiring the user to carry a wireless device
What are some problems with WiTrack?

How would you improve it?

Societal implications
Who is behind the wall?
How is the person standing?
Writing in the air

Device

Our Tracking Result

Kinect (in red)
AI Senses People Through Walls
Remotely Measuring Breathing and HR

[CHI’15]
Idea: Use wireless reflections off the human body

Measure the distance to the human body
Problem: Localization accuracy is only 12cm and cannot capture vital signs

Wireless device

Why? How did we compute the resolution?
Wireless device analyzes the wireless reflections to compute distance to the body. Problem: Localization accuracy is only 12cm and cannot capture vital signs. Why does phase allow us to get the distance at higher granularity? Solution: Use the phase of the wireless reflection.
Solution: Use the phase of the wireless reflection

Wireless device

Why did we need FMCW if phase is so accurate?

Wireless wave has a phase: \( \phi = 2\pi \frac{d_{\text{inhale}}}{\lambda} \)

- Chest Motion changes distance
- Heartbeats also change distance

Problem: Localization accuracy is only 12cm and cannot capture vital signs

Solution: Use the phase of the wireless reflection

Why did we need FMCW if phase is so accurate?
Let’s zoom in on these signals
Baby Monitoring
Accuracy vs. Orientation

User is 4m from device, with different orientations

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Breathing Rate</th>
<th>Heart Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward</td>
<td>99.1</td>
<td>96.7</td>
</tr>
<tr>
<td>Right</td>
<td>97.4</td>
<td>96.6</td>
</tr>
<tr>
<td>Backward</td>
<td>97.7</td>
<td>97.7</td>
</tr>
<tr>
<td>Left</td>
<td>97.7</td>
<td>97.6</td>
</tr>
</tbody>
</table>
Recent Advances

• Emotion Recognition
• Sleeping Monitoring  
  – Positions, staging, timing  
• Daily activities & action recognition  
• Patient Movement Monitoring: Alzheimer’s, Parkinson’s, Multiple Sclerosis  
• Cardiovascular Monitoring (Micro-cardiac events)
Wi-Fi Becomes Sound Backbone for Motion Sensing and Smart-Home Monitoring

November/December 2019

By Oleksiy Kravets | Cognitive Systems

Service providers should look to the emerging motion-sensing and smart home market for new opportunities.

Network World

Cisco moves WiFi roaming technology to wireless broadband consortium

Synced

Samsung AI Uses WiFi Signals to Generate Consistent In-Home User Localization Data

Gizmodo

Motion Sensing Wifi Is a Limited But Fascinating Peek at the Future of the Smart Home
Main Components of IoT Systems

Axis #1: Power/Energy

Axis #2: Connectivity

Axis #3: High-level Task (Sensing, Actuation)

So Far Lecture

Rest of Lecture
Underwater-to-Air Comm Applications

Submarine-Airplane Communication

Finding Missing Airplanes

Ocean Scientific Exploration
Underwater-to-Air Comm Applications

Why is it difficult?
Submarines Cannot Communicate with Airplanes
Direct Underwater-Air Communication is Infeasible
Direct Underwater-Air Communication is Infeasible

Wireless signals work well only in a single medium
Wireless Signals Work Well Only in a Single Medium
Wireless Signals Work Well Only in a Single Medium

Radio

Acoustic or SONAR
Use Acoustic signals?

Reflects off the Surface

Acoustic
Use Acoustic signals?

Reflects off the Surface

Use Radio Signals?

Radio Signals Die in Water

Acoustic

Radio
What are today’s approaches for solving this problem?
Approach #1: Relay Nodes

[OCEANS’07, ICC’11, ICC’14, Sensors’14]
Approach #1: Relay Nodes

[OCEANS’07, ICC’11, ICC’14, Sensors’14]
Approach #2: Surfacing
[ICRA’06, MOBICOM’07, OCEANS’10, ICRA’12]
First Technology that Enables Wireless Communication Across the Water-Air Boundary

How does it work?
First Technology that Enables Wireless Communication Across the Water-Air Boundary
Translational Acoustic RF Communication (TARF)
Translational Acoustic RF Communication

First technology that enables wireless communication across water-air interface

Theoretically achieves the best of both RF and acoustic signals in their respective media

Deals with practical challenges of communicating across water-air interface including natural surface waves

Implemented and tested in practical environments
Key Idea

Surface Vibration

RADAR

Acoustic

Underwater speaker
Can We Sense the Surface Vibration Caused by the Transmitted Underwater Acoustic Signal?
Recording the Surface Vibration

**Experiment:** Transmit Acoustic Signals at 100Hz
Recording the Surface Vibration

Experiment: Transmit Acoustic Signals at 100Hz

Underwater Speaker
How Can We Sense Microscale Vibration?

Idea: Use RADAR to measure the surface vibration
How Can We Sense Microscale Vibration?

Idea: Use RADAR to measure the surface vibration

Problem: Measuring micrometer vibrations requires 100s of THz of bandwidth → Impractical & Costly
Solution: Measure Changes in Displacement Using the Phase of Millimeter-Wave RADAR
Solution: Measure Changes in Displacement Using the Phase of Millimeter-Wave RADAR

The phase of the millimeter-wave RADAR encodes transmitted information from underwater.

Phase = $360 \times \frac{\text{displacement}}{\text{wavelength}}$

Phase Variation = 0.72 degrees

Phase Variation = 0.72 degrees
Natural Surface Waves Mask the Signal

On Calm Days, Ocean Surface Ripples (Capillary Waves) Have 2cm Peak-to-Peak Amplitude

1,000 Times Larger than Surface Vibration Caused by the Acoustic Signal
Natural Surface Waves Can Be Treated as Structured Interference and Filtered Out

Naturally occurring waves (e.g., ocean waves) are relatively slow

Acoustic signals are transmitted at higher frequencies

Frequency

1 – 2Hz

100 – 200Hz
Natural Surface Waves Can Be Treated as Structured Interference and Filtered Out
Natural Surface Waves Can Be Treated as Structured Interference and Filtered Out

Filtering alone does not work

Natural Surface Waves

Frequency (Hz)
Dealing with Waves

\[ \text{Angle} = 360 \times \frac{\text{displacement}}{\text{wavelength}} \]
Dealing with Waves

\[ \text{Angle} = 360 \times \frac{\text{displacement}}{\text{wavelength}} \mod 360 \]
Dealing with Waves

\[ \text{Angle} = 360 \times \frac{\text{displacement}}{\text{wavelength}} \mod 360 \]

Diagram showing wave displacement with a 5mm peak-to-peak amplitude. The wave wraps around at certain time intervals (0.5, 1, 1.5, 2, 2.5, 3, 3.5 seconds).
Dealing with Waves

![Wave diagram with displacement (cm) on the y-axis and time (sec) on the x-axis.]
Dealing with Waves

Track & Unwrap

Trend is Water Surface Wave

Transmitted signal

2cm
Dealing with Waves

Track & Unwrap

Filter

Filtered Surface Vibration
Dealing with Waves

By treating natural surface waves as structured interference, we are able to track and eliminate their impact on our signal.
How Can We Decode?

Filtered Surface Vibration

Time (sec)

displacement (cm)

0? 1?
Simple Modulation schemes

ON-OFF keying, FM0/Manchester, FSK
Decoding Information

RADAR

Underwater Speaker

Angle Variation

100Hz

Surface Vibration

100Hz

Rx

200Hz

Rx

Bit 0

Tx: 100Hz

Bit 1

Tx: 200Hz

100Hz
Standard Modulation Schemes?

The wireless channel
Mathematics & Physical Interpretation
Upconversion & Downconversion

Modulation & Demodulation