COS 597E: Neural Sensing, Modeling, and Understanding

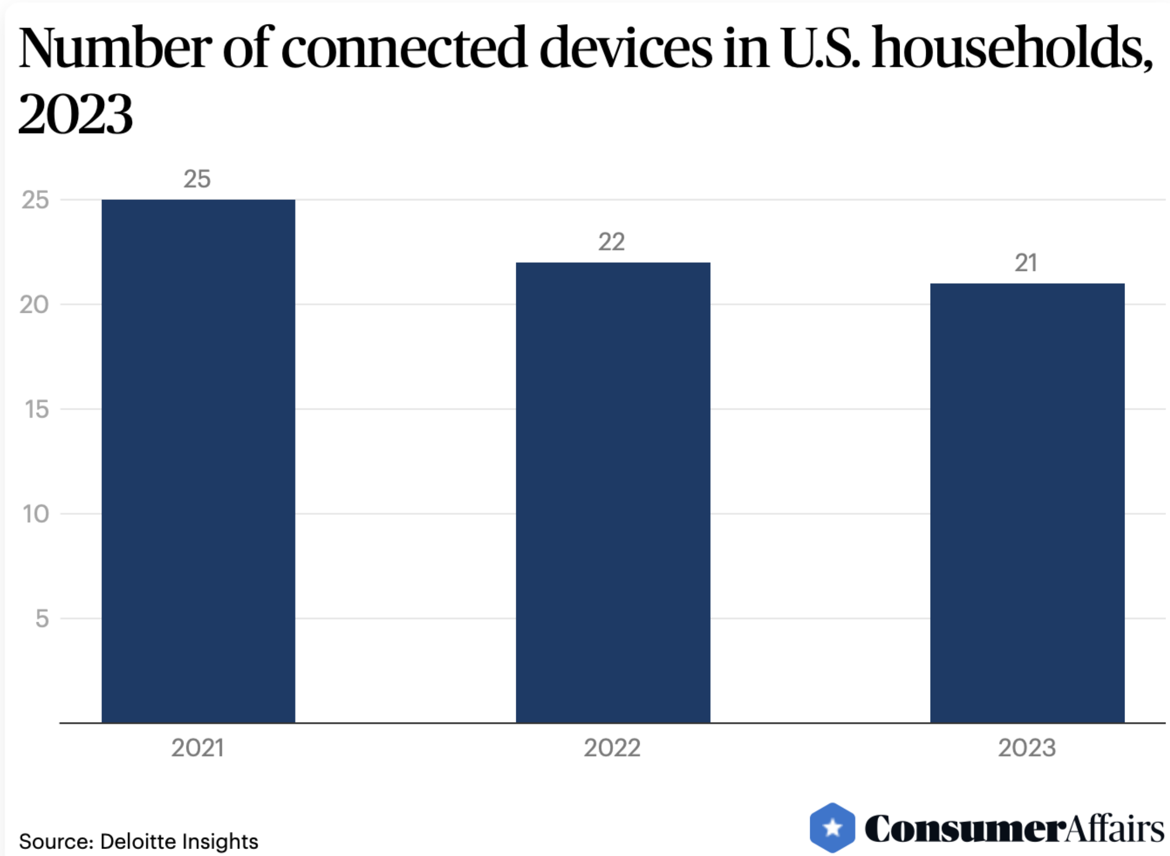
Kyle Jamieson

Fall 2025

No phones, tablets, AR glasses, or Neuralink!

LET’S START WITH AN OVER/UNDER GAME

IoT devices per U.S. household (average)



8?

Number of mobile phones per person

1?

Rankings	Country or regions	# of phone numbers	Population	Phone #'s/100 citizens	Date of evaluation
World		7,950,000,000+	7,621,018,958	104.32	2019/12[1][2]
1	China	1,610,360,000	1,420,050,000	113.38	2020/10[3][4]
2	India	1,515,971,713	1,375,245,994	110.18	2020/10[3][5]
3	Indonesia	385,573,398	237,556,363	162.28	2016/07[6]
4	United States	380,577,528	327,874,628	116.27	2020/10[7][8]
5	Brazil	284,200,000	201,032,714	141.3	2015/05[6][9]
6	Russia	256,116,000	142,905,200	155.5	2013/07[6][10]
7	Pakistan	196,017,287	241,422,083	80.1	2024/12[11][12]
8	Nigeria	190,475,494	190,551,754	99.5	2020/04[13]
9	Bangladesh	180,780,000	162,951,560	111.11	2022/03[14]
10	Japan	146,649,600	127,300,000	115.2	2013[15]
11	Germany	107,000,000	81,882,342	130.1	2013[16]
12	Philippines	106,987,098	94,013,200	113.8	2013/10[17]
13	Mexico	101,339,000	112,322,757	90.2	2013/07[18]

Autonomous vehicle accident rate

Human-Driven vehicle accident rate?

Article | Open access | Published: 18 June 2024

A matched case-control analysis of autonomous vs human-driven vehicle accidents

Mohamed Abdel-Aty & Shengxuan Ding

Nature Communications **15**,

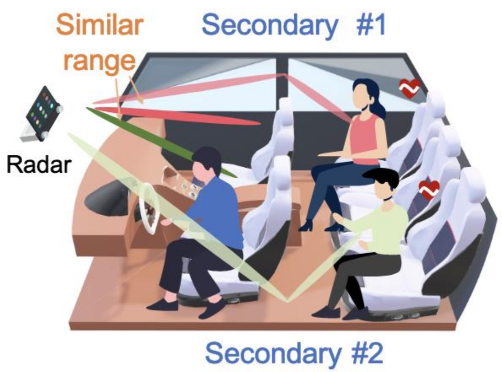
accidents. The analysis suggests that accidents of vehicles equipped with Advanced Driving Systems generally have a lower chance of occurring than Human-Driven Vehicles in most of the similar accident scenarios. However, accidents involving Advanced Driving Systems occur more frequently than Human-Driven Vehicle accidents under dawn/dusk or turning conditions, which is 5.25 and 1.98 times higher, respectively. Our

Number of U.S. states (out of the lower 48 states) with long haul fiber comms links?

48?

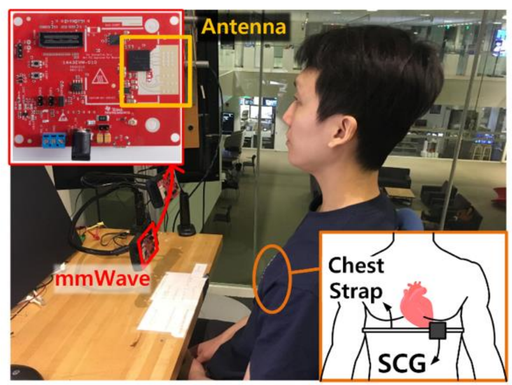
Neural Sensing, Modeling, and Understanding

Human Activity Recognition



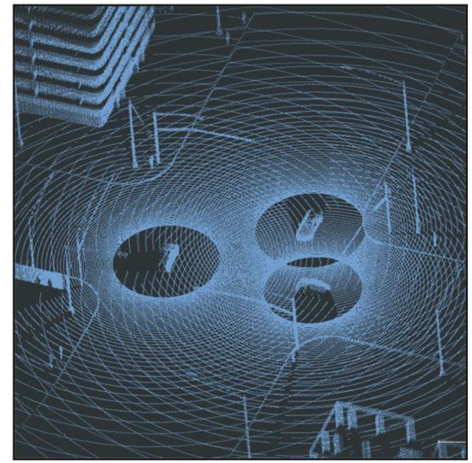
(Wi-Fi, mmWave)

e-Health: seismocardiogram, spirometry, heartrate



(Mobile devices, mmWave)

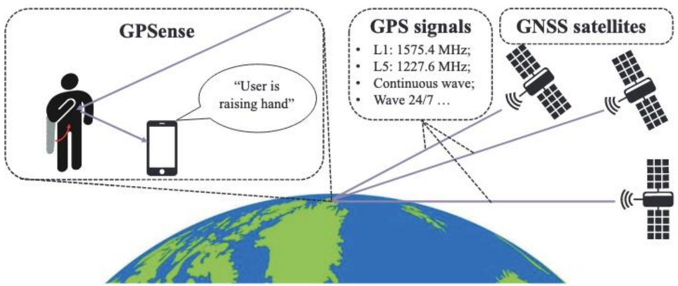
Vehicular Navigation & Situational Awareness



(LIDAR, Vision, mmWave)

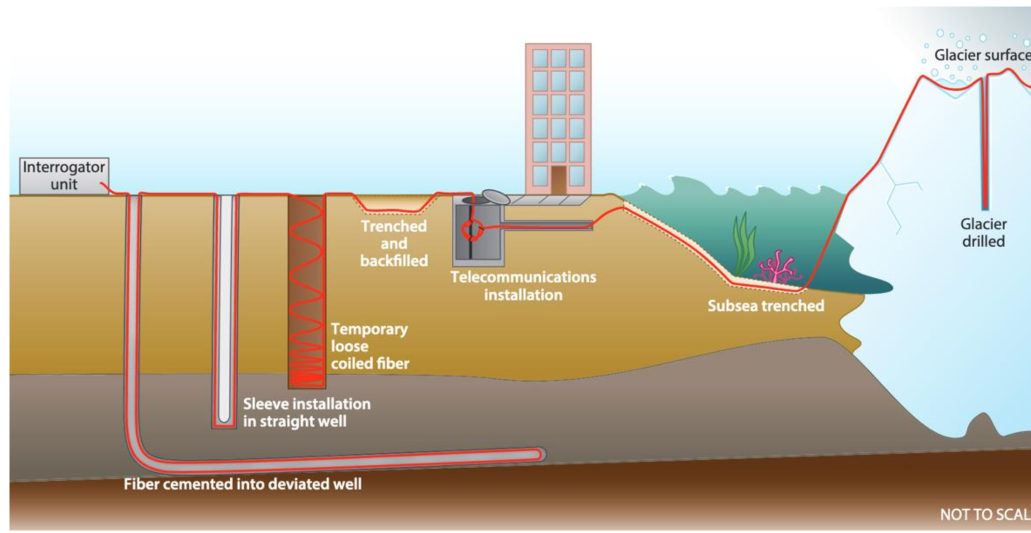
Neural Sensing, Modeling, and Understanding

Ambient Sensing (Integrated Sensing & Communication)



(Wi-Fi, mmWave, LoRA, GPS)

Sensing with Optical Fiber: Smart Cities, Oceans, Glaciers



Today

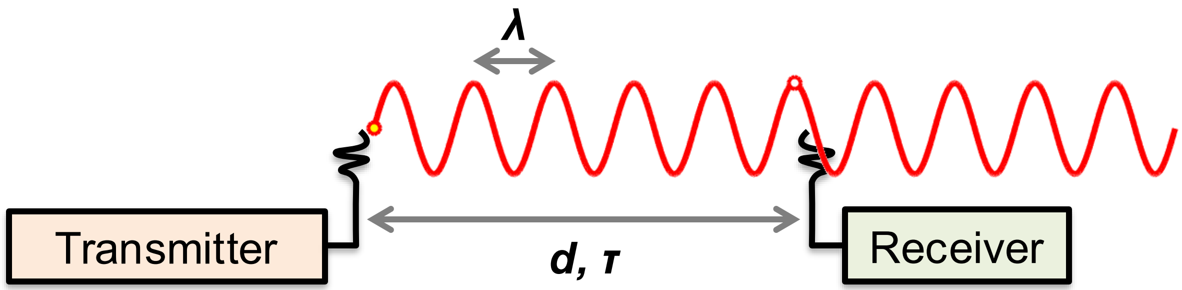
- **The Wireless Channel**

- Today's "Pre-read:" Sionna Ray Tracer (RT)

- Administrivia

Sinusoidal carrier, line of sight only

- Suppose **transmitter** is **distance *d*** (**propagation time delay *τ* = *d* / *c***) away from **receiver** (where *c* is the speed of light)

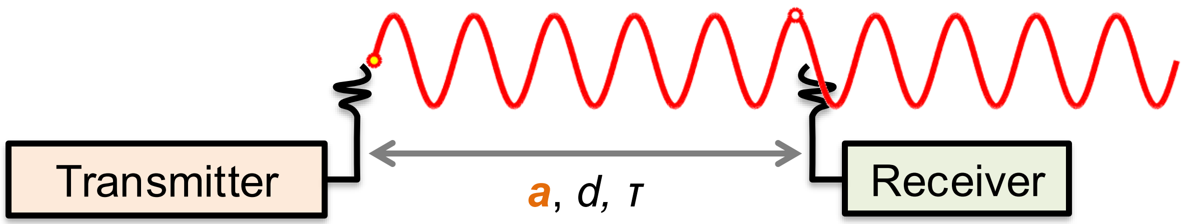


- Radio frequency transmitted signal: $\cos(2\pi f_c t) = \cos(2\pi c/\lambda \cdot t)$
  - Carrier frequency f_c corresponds to ***radio wavelength λ***
  - **Baseband** transmitted signal **in one symbol period:** $x = 1 + 0j$

What is the effect of the channel?

Sinusoidal carrier, line of sight only: Signal Attenuation

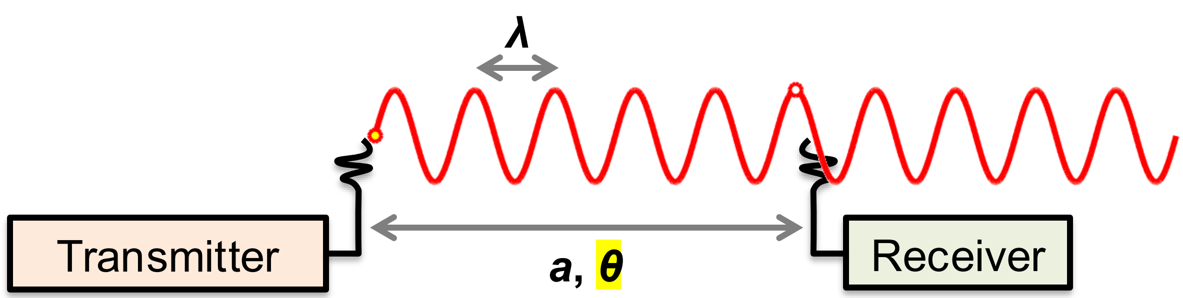
- Represent channel's amplitude ***attenuation*** with a real number ***a***



- *e.g.* attenuation due to two refractions and partial reflection as the signal passes through an indoor wall

Sinusoidal carrier, line of sight only: Signal Phase Shift

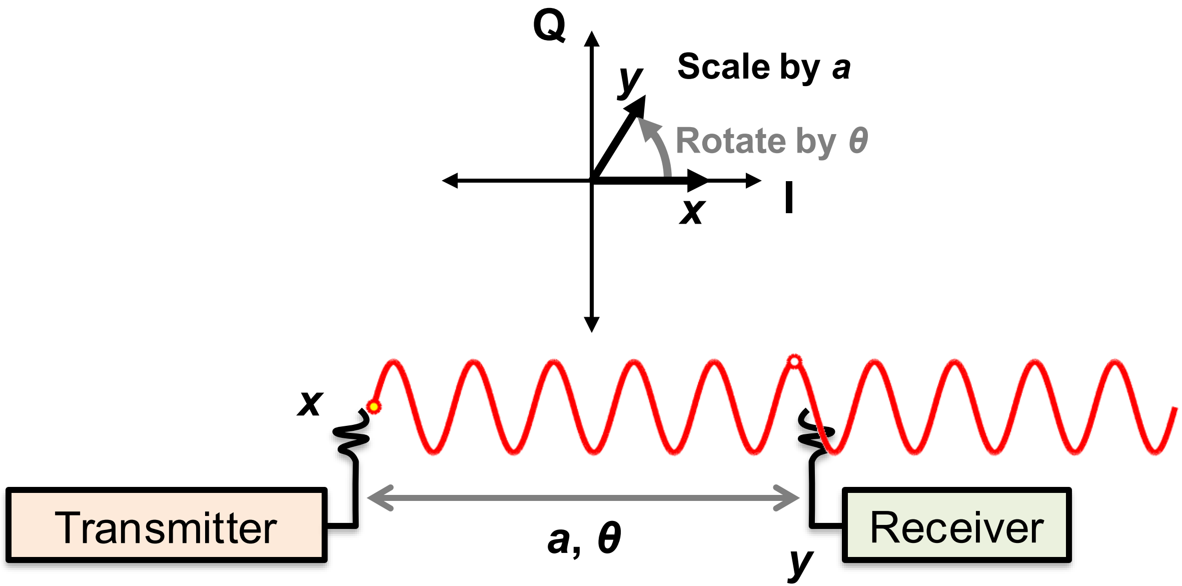
- Received signal **travels some distance *d***
- **One wavelength** corresponds to a 360˚ (**2π radian**) **phase shift**
- Represent path's **phase shift** with an **angle** (real number) $\boldsymbol{\theta = 2\pi \cdot d / \lambda}$
  - "Abstract away" distance and wavelength into (one) phase shift θ



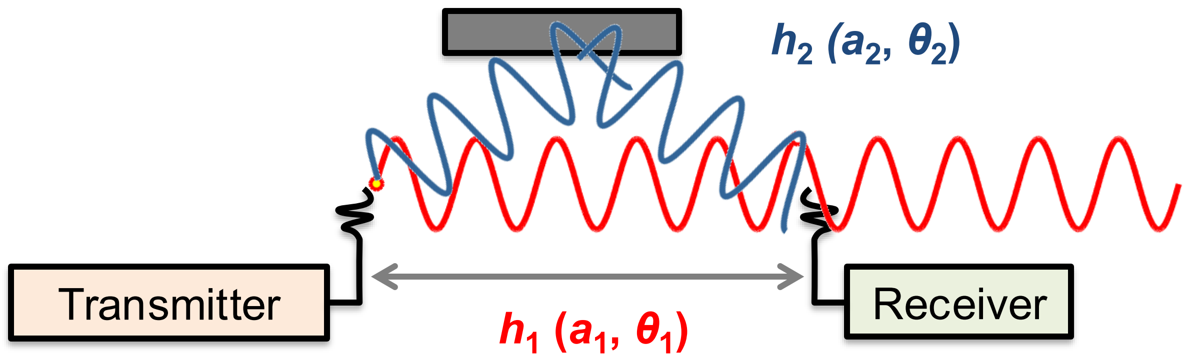
Sinusoidal carrier, line of sight only: Channel Model

- *Wireless channel h* **attenuates by *a*, phase-shifts by *θ***
  - Therefore, $h = ae^{j\theta}$

- **Received baseband signal:** $y = h \cdot x$ (no noise)



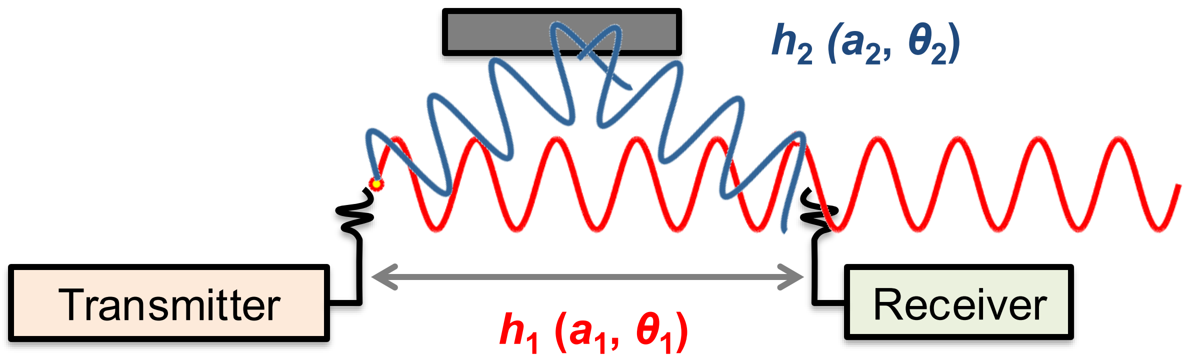
Line-of-sight plus reflecting path: Motivation



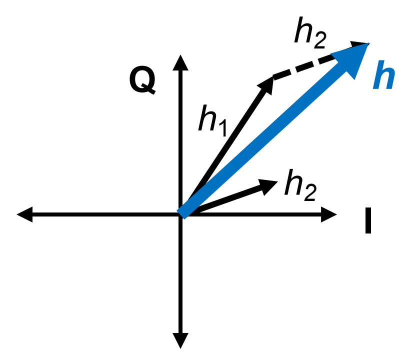
- What if reflections (*e.g.*, indoor walls) introduce a second path?

- Wireless channel becomes the **superposition** of the ***direct path's channel h_1*** and the ***reflection path's channel h_2***

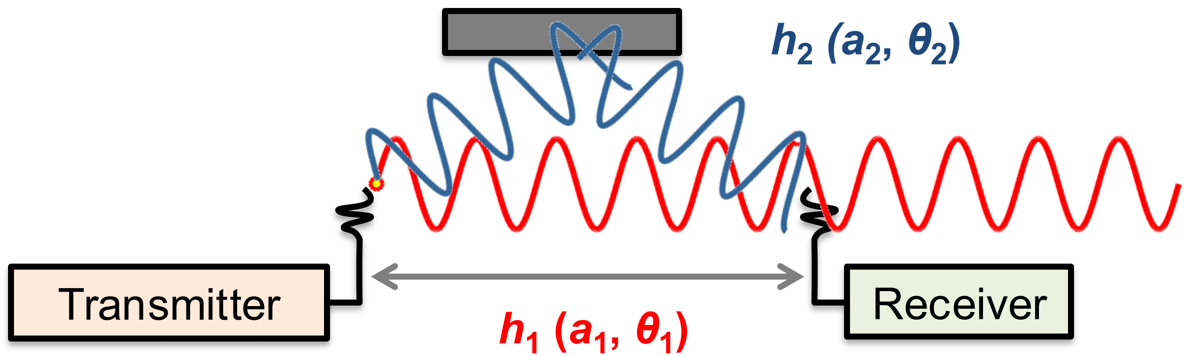
Line-of-sight plus reflecting path: Channel Model

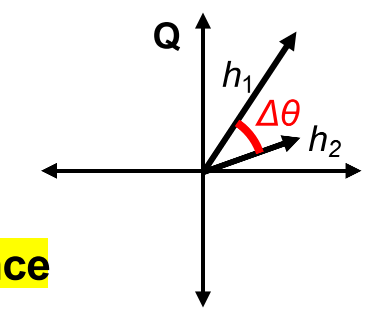


- Channel is now $h = h_1 + h_2 = a_1 \, e^{j\theta_1} + a_2 e^{j\theta_2}$



Line-of-sight plus reflecting path: Channel Model

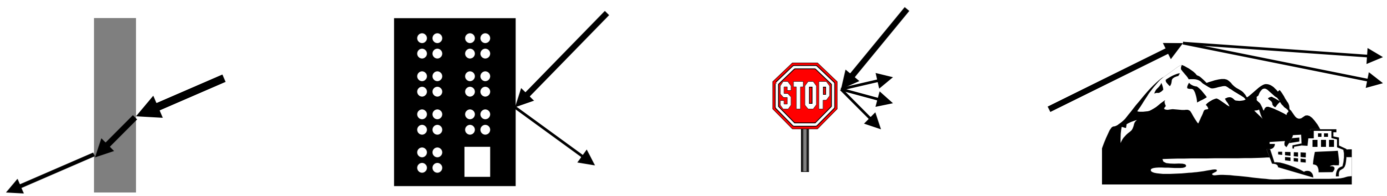




- ***Phase difference between paths*** $\Delta\theta = 2\pi/\lambda(d_1 - d_2)$
  - Depends on **wavelength** and **path length difference**

- **So,** $|h|$ **depends on wavelength (frequency)** as well as channel attenuation

Radio Propagation Mechanisms

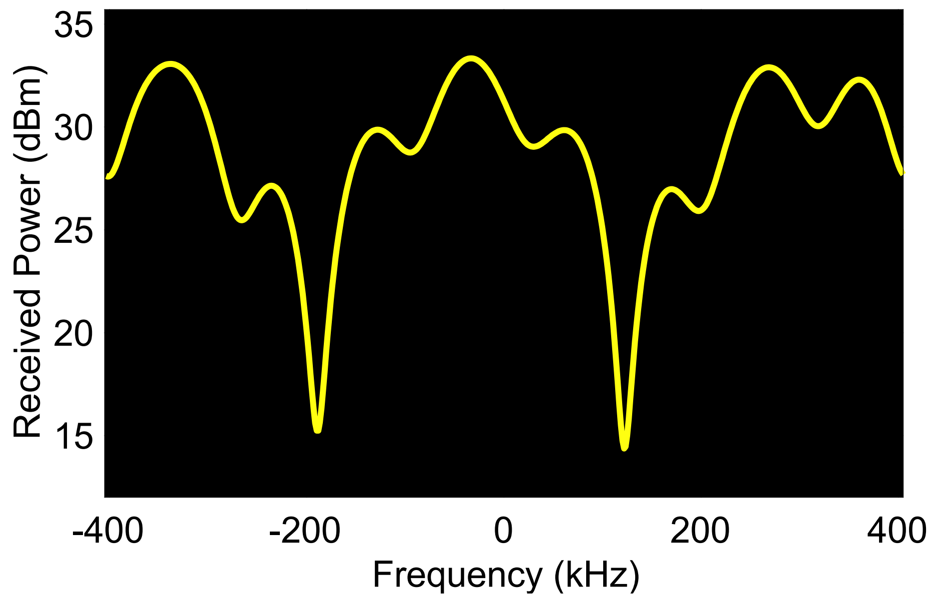


Refraction Reflection Scattering Diffraction

- **Refraction:** Propagation wave changes direction when impinging on different medium
- **Reflection:** Propagation wave impinges on **large object (compared to λ)**
- **Scattering:** Objects **smaller than λ** (i.e. foliage, street signs etc.)
- **Diffraction:** Transmission path obstructed by surface with **sharp irregular edges**
  - Waves **bend around obstacle**, even when line of sight does not exist

Reflections cause frequency *selectivity*

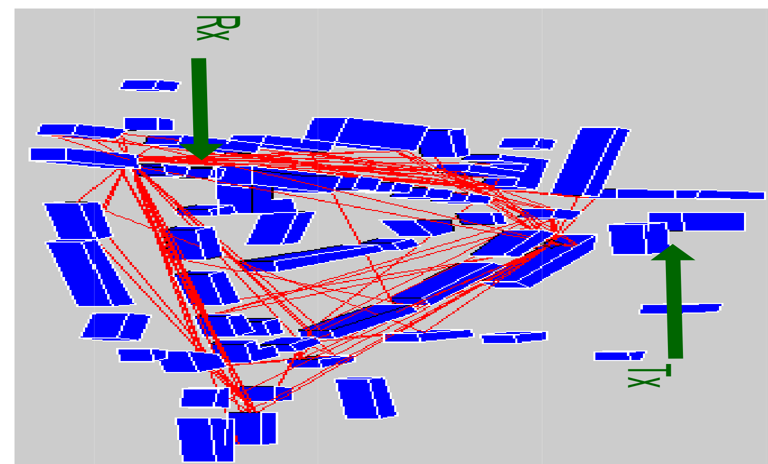
- Interference between reflected and line-of-sight radio waves results in **frequency dependent fading**



- ***Coherence bandwidth*** B_c: **Frequency range** over which the channel is roughly the **same** ("flat")

Putting it all Together: Ray Tracing

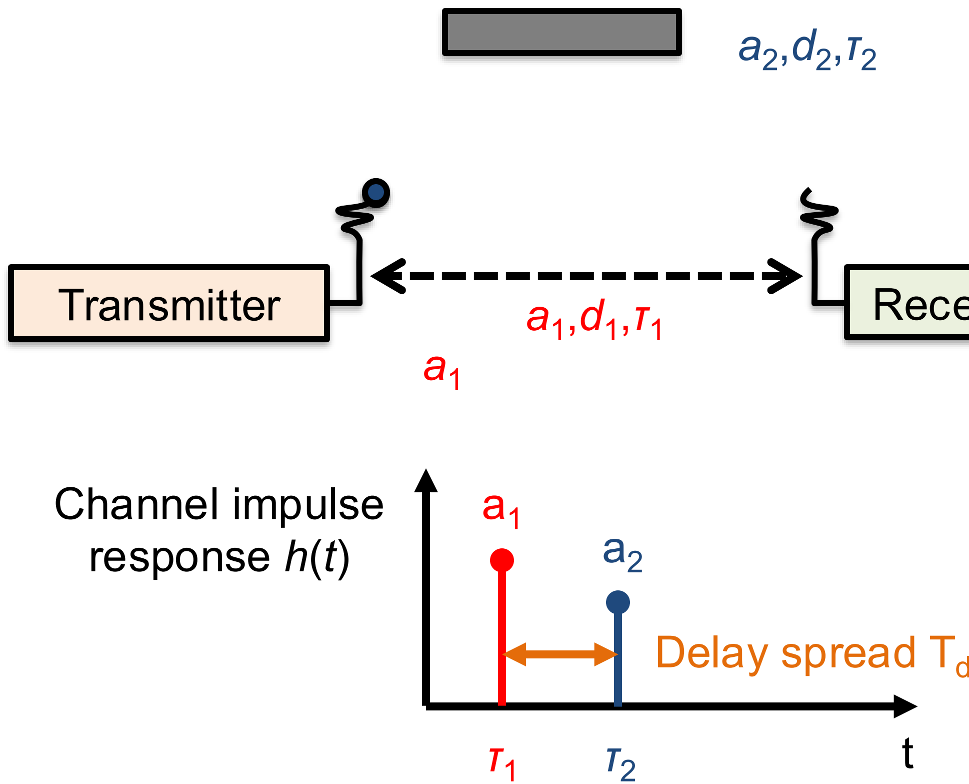
- Approximate solutions to Maxwell's equations → **represent wavefronts as particles, traveling along rays**
  - **Geometric** reflection, diffraction, scattering **rules** compute ∡ reflection, diffraction
- Error smallest when **receiver ≫ λ from nearest scatterer,** size **objects ≫ λ**
- Good match to empirical data in rural areas, along city streets, and indoors
- **Completely site-specific:** movement **invalidates model**



Today

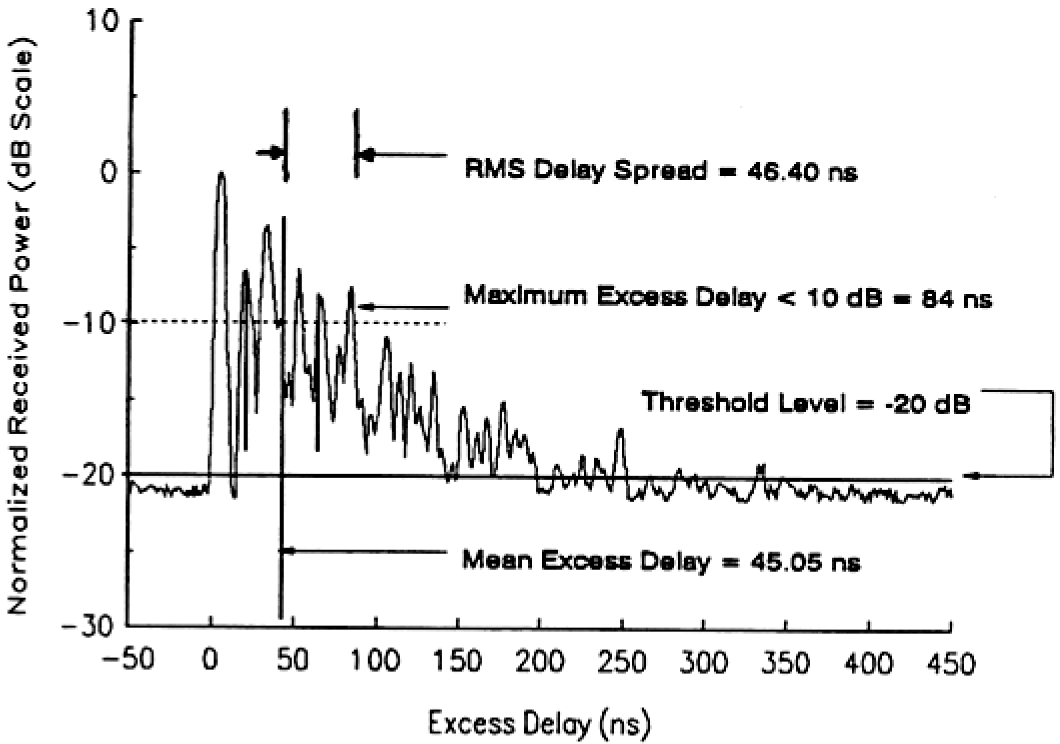
- **The Wireless Channel**
  - **Multi-path propagation**
    - Frequency-domain view
    - **Time-domain view**
  - Motion and channel coherence time
- Today's "Pre-Read:" Sionna Ray Tracer (RT)
- Administrivia

What does the channel look like in time?



Power delay profile- Measurements

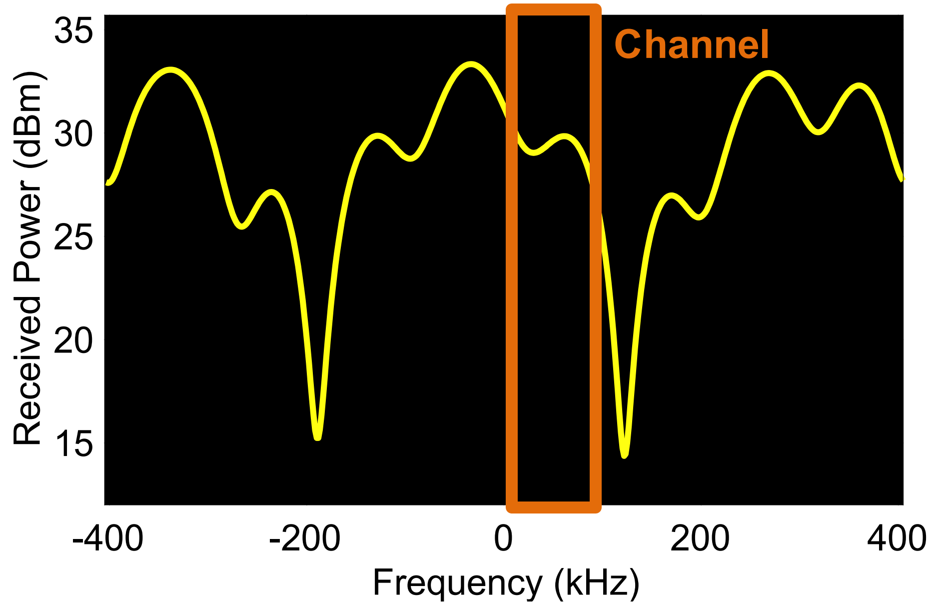
- **Power** received via the path with **time delay** τ_i is the value (height) of the discrete PDP component $P(\tau_i) = |h(\tau)|^2$ at τ_i



Typical RMS delay spreads

Environment	RMS delay spread
Indoor cell	10 – 50 ns
Satellite mobile	40 – 50 ns
Open area (rural)	< 0.2 µs
Suburban macrocell	< 1 µs
Urban macrocell	1 – 3 µs
Hilly macrocell	3 – 10 µs

Flat Fading



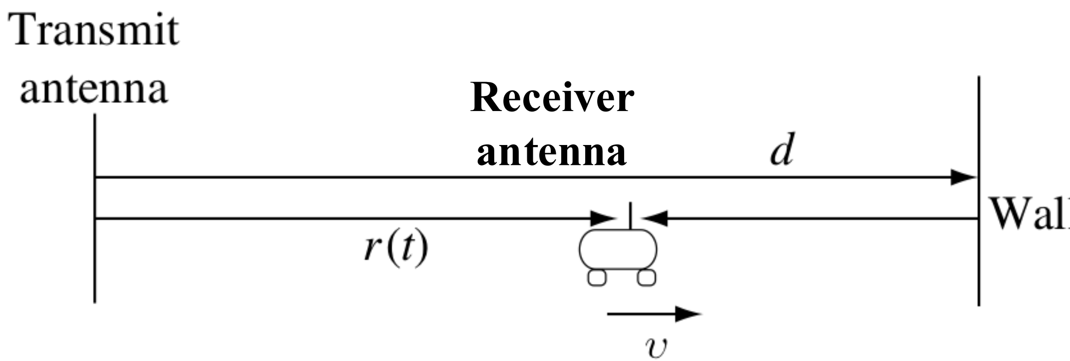
Not shown above!

- Slow down → sending data over a **narrow bandwidth** channel
  - Channel is **constant** over its bandwidth
  - **Multipath is still present,** so channel strength fluctuates **over time**
    - **How to model this fluctuation?**

Today

- **The Wireless Channel**
  - Multipath propagation
  - **Motion and channel coherence time**
- Sionna Ray Tracer (RT)
- Administrivia

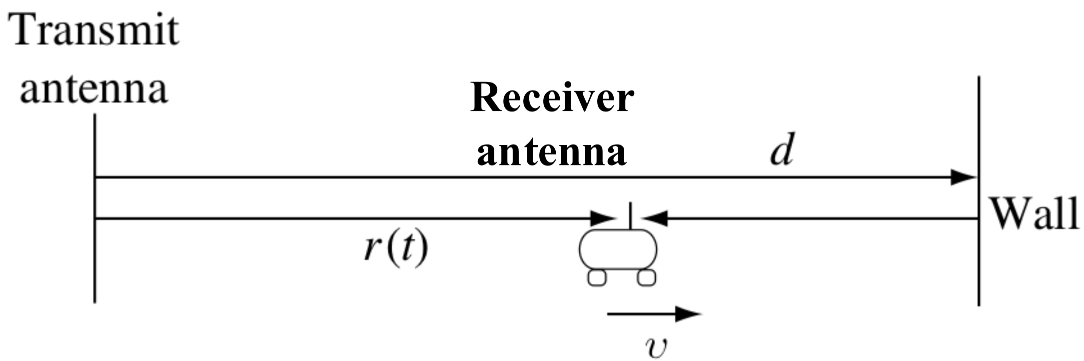
Stationary transmitter, moving receiver



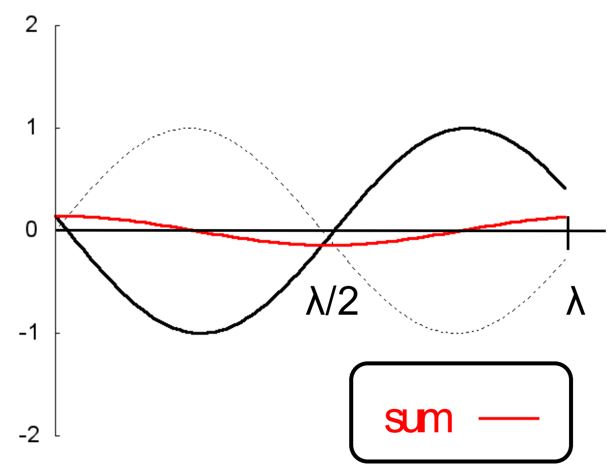
- Suppose **reflecting wall**, fixed transmit antenna, no other objects
  - Receive antenna moving rightwards at velocity v

- **Two arriving signals** at receiver antenna with a **path length difference of** $2(d - r(t))$

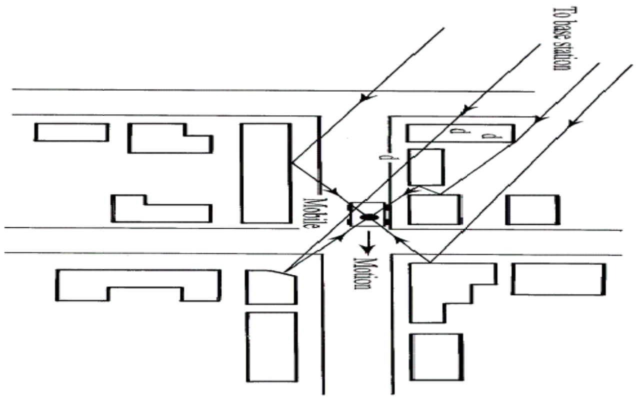
How does fading in time arise?

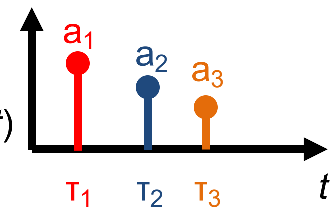


- **Path length difference** $\Delta = 2(d - r(t))$
- If $\Delta \pmod{\lambda} = \frac{\lambda}{2}$ → receive ≈ 0
  - ***Destructive interference***
- If $\Delta \pmod{\lambda} = 0$ → receive ≈ 2
  - ***Constructive interference***



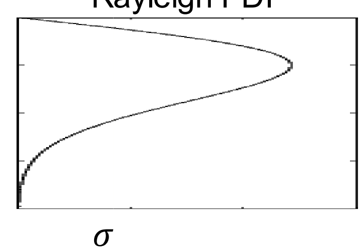
Rayleigh Fading Model





- Random gain of k^{th} arriving path: $a_k = a_k^I + ja_k^Q$
- Therefore, the I and Q **channel components** h_I, h_Q are **zero-mean Gaussian distributed**
- So $|h| = \sqrt{h_I^2 + h_Q^2}$ is ***Rayleigh-distributed***

Rayleigh PDF



Rayleigh fading example

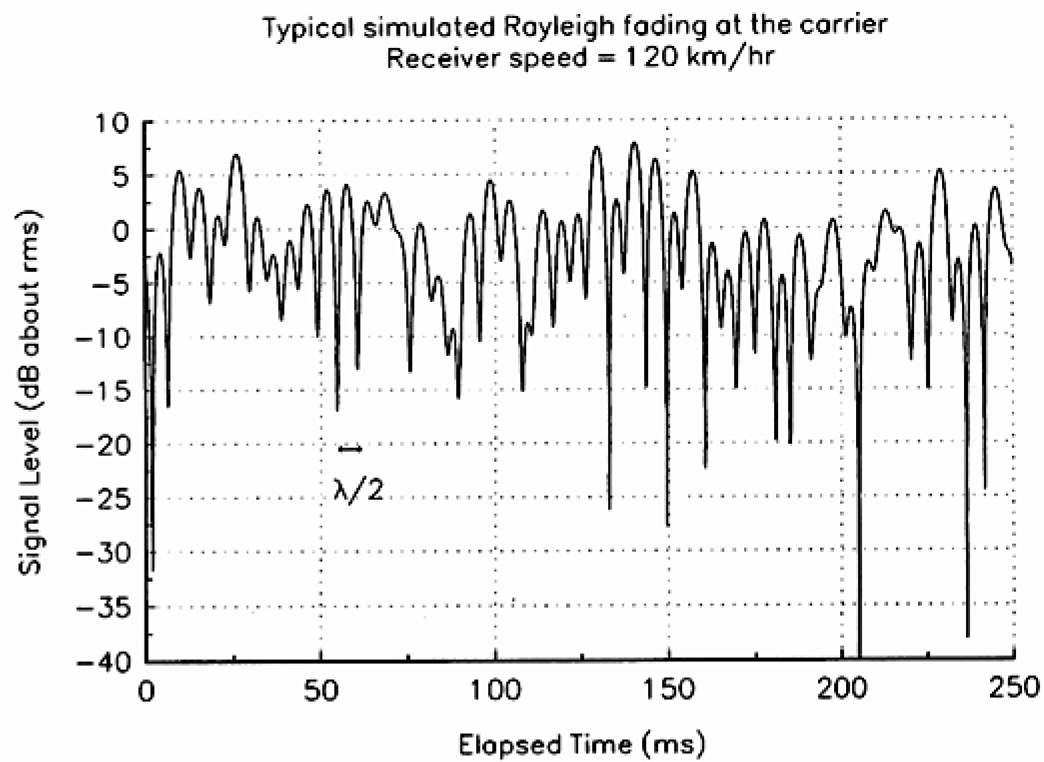


Figure 5.15 A typical Rayleigh fading envelope at 900 MHz [from [Fun93] © IEEE].

Channel Coherence Time

- **A change** in **path length difference** of λ / 2 transitions from constructive to destructive interference
  - Receiver movement of **λ/4:** ***coherence distance***
  - **Duration of time** that transmitter, receiver, or objects in environment take to move a coherence distance: ***channel coherence time*** T_c
    - Walking speed (2 mph) @ 2.4 GHz: ≈ 15 milliseconds
    - Driving speed (20 mph) @ 1.9 GHz: ≈ 2.5 milliseconds
    - Train/freeway speed (75 mph) @ 1.9 GHz: < 1 millisecond

Today

- The Wireless Channel
- **Sionna Ray Tracer (RT)**
- Administrivia

Sionna RT: Differentiable Ray Tracing for Radio Propagation Modeling

- Ray Tracing: use cases
  - Simulate a **specific environment** for an experiment
  - **Digital twins:** model the real world in real-time with feedback

- Mature field; **but** ML techniques promise **to improve accuracy and increase speed**

- **Differentiable** ray tracer: **outputs** can be **differentiated** with respect to the **object material parameters** of the simulation

Relevant properties of materials in ray-tracing simulation?

- (Given radio frequency *f*; angular frequency $\omega = 2\pi f$)

- **Conductivity** σ: measures material's ability to conduct electric current

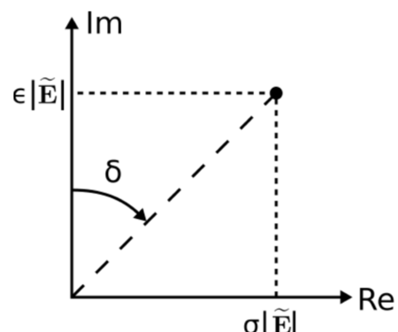
- **Permittivity** ε: measures material's ability to store electric energy (**permittivity relative to free space** is denoted *η*)

Attenuation in a material

Conductivity σ
Permittivity ε/η

- Wave going through material with $\sigma \neq 0$
- Maxwell's equations tell us velocity of the wave $$v = \frac{c}{\sqrt{\eta}}$$
- And, Maxwell's equations can be rearranged: $$\frac{c^2}{v^2} = \eta - j\frac{\sigma}{\varepsilon_0 \omega}$$
- **Loss tangent** tan δ depends on conductivity and permittivity

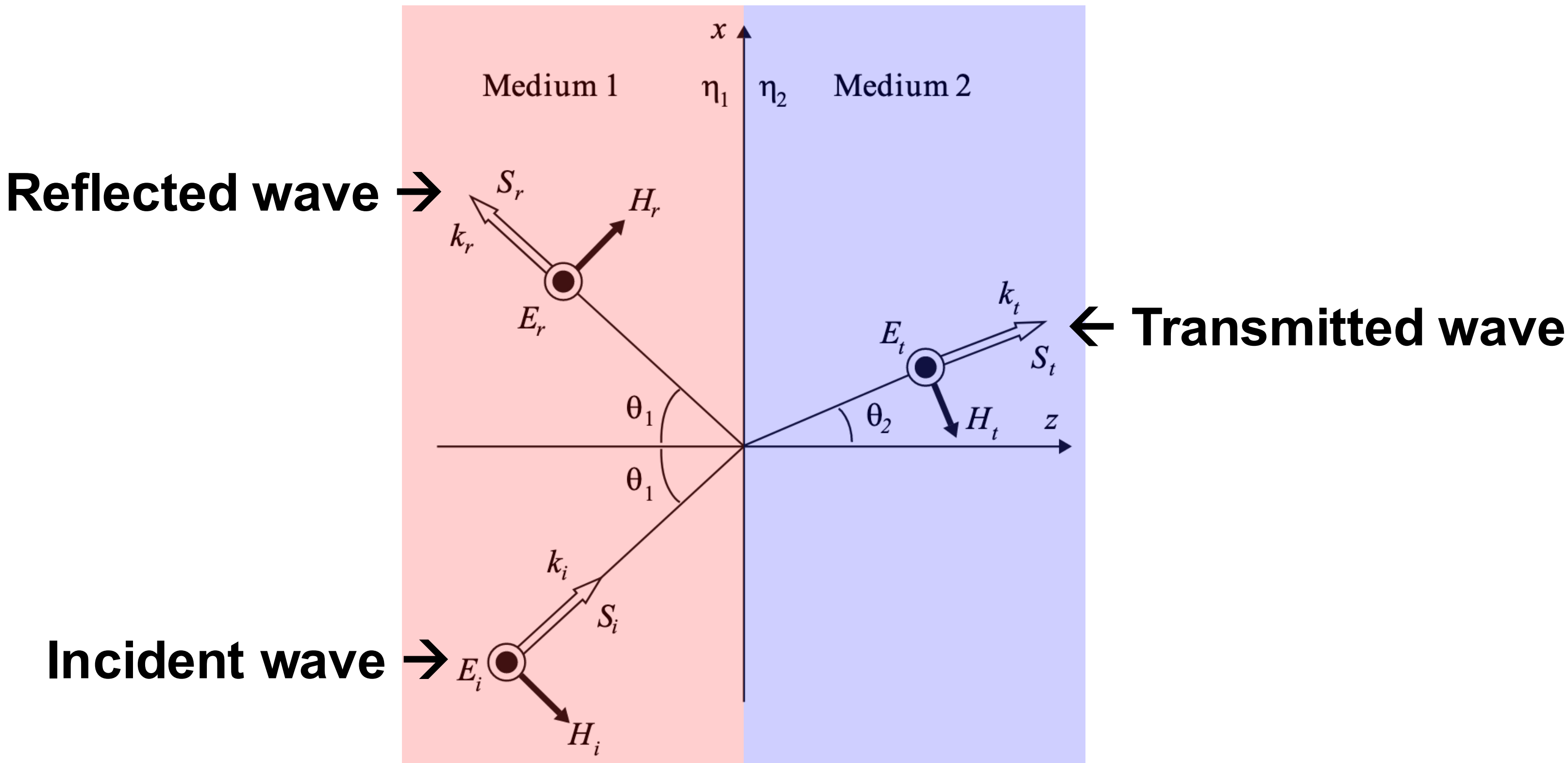
Define this: **complex relative permittivity**



Reflection & transmission at an interface

Conductivity σ
Permittivity ε/η

- **Interface:** boundary between two materials or air & material

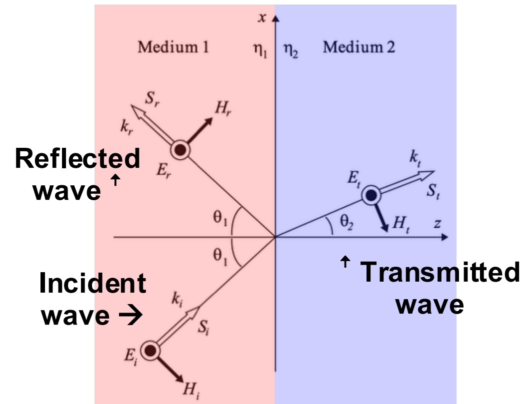


Reflection & transmission depend on material properties

Conductivity σ
Permittivity ε/η

- **Angle of transmission depends on** angle of incidence & ratio of permittivities:

$$\cos\theta_2 = \sqrt{1 - \frac{\eta_1}{\eta_2}\sin^2\theta_1}$$



- **Reflection coefficient** Er/Ei depends on angle of incidence and both permittivities

- **Transmission coefficient** Et/Ei depends on angle of incidence and both permittivities

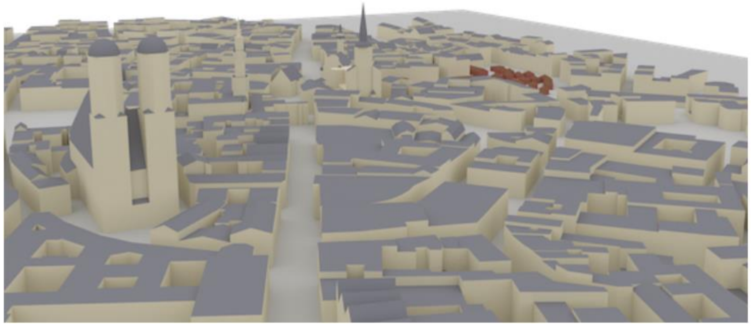
See "Effects of building materials and structures on radiowave propagation above about 100 MHz" in Zotero for equations

Sionna RT: Design

- Start with **Mitsuba 3** graphics rendering package
  - **Compute** radio ray **intersection locations** with objects

- **TensorFlow** computes the transformations of the radio rays when they hit objects using material parameters

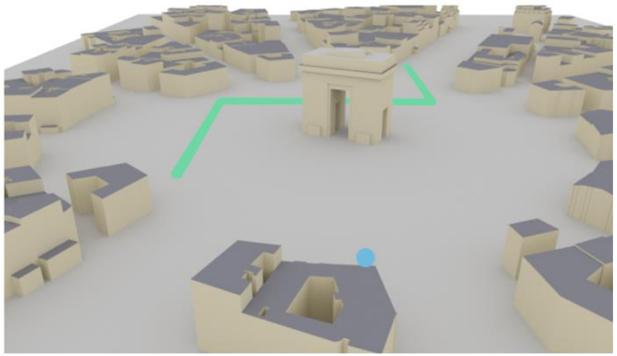
- Example urban scene from OpenStreetMap:



Learning Radio Materials: Setting

- Problem- OpenStreetMap lacks material parameters

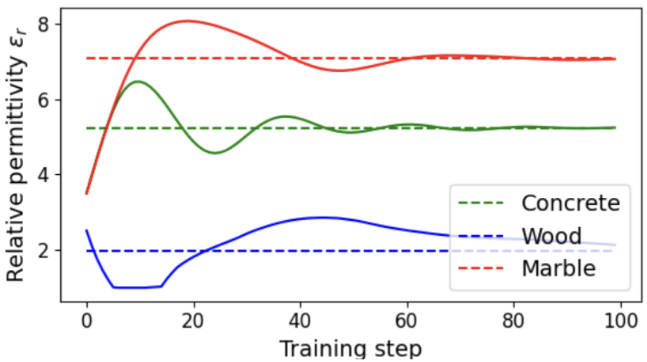
- **Setting:** one transmitter, 400 receivers in an urban scene
  - Concrete streets, marble walls, metal roofs, wood ceiling Arc

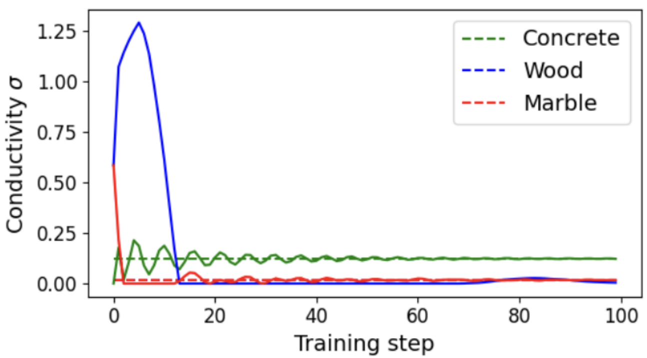


- ***Simulate*** *"ground truth"* channel measurements with the above material parameters (ε, σ)

Learning Radio Materials

- Initialize all objects with default values, then gradient descent on the error between the simulated and "ground truth" channels





- Dashed lines: "ground truth"
- Solid curves: gradient descent trajectories
- **Limitation:** the ground truth was simulated; learning occurred in same simulation

Today

- The Wireless Channel
- Sionna Ray Tracer (RT)
- **Administrivia**

Webpage, Instructor, Office Hours

Webpage: kyleatprinceton.github.io/cos597e-f25

- **Instructor:** Kyle Jamieson, CS room 306
  - Office hours by appointment

- **Meetings:** 301 CS, Tuesday/Thursday 3:00–4:20 PM

Prerequisites

- **Open** to graduate students
  - CS, ECE students who want to extend their background

- **Open** to undergraduates with background
  - And with permission of the instructor
  - **COS 461**, **ECE/COS 368 , COS 333, COS 318** all helpful

kyleatprinceton.github.io/cos597e-f25

Goals of the Seminar

1. Understand **state of the art:** sensing with neural nets using multimodal data (some wireless, some optics)

2. Understand how to **do research in wireless**
   – How to read a paper, search wireless literature

3. Investigate **novel ideas** in the above areas through a **hands-on, semester-long** research project

kyleatprinceton.github.io/cos597e-f25

Soft Outcomes

- To develop **taste** and **"systems maturity"** in research
  - What constitutes a good research problem?
  - What constitutes convincing scientific evidence that a design solves a problem?

- To develop skills in **delivering clear technical explanations** in informal settings
  - Might be encountered during one-on-one job interview meetings with engineers or academics
  - Or in grad school, or at work

Course Contents

- **Research Paper Discussions:** Dive into sub-areas

  – Exercise **critical thinking** on **exciting current research**
    - Compare proposed solutions
    - Discuss applicability and limitations

- **Term Project:** individual or in pairs, hands-on
  – Topic is flexible; chosen in consultation with me

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Research Paper Readings: Online Discussion Period

- Available on webpage → **Perusall** platform
  - Read papers ahead of time
  - Online discussion on Perusall
  - ~5 substantive comments/replies, **quality > quantity**

- Half of your class participation grade:
  - Contribute <u>thoughtful</u> questions & comments
  - Questions/comments that elicit responses
  - Answering questions from others, upvoting others

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Research Paper Readings: Class Meeting Discussion

- Come to class meeting prepared to discuss:
  1. What problem is the paper solving , why is problem important?
  2. What was the previous state of the art and how does this paper advance that state of the art?
  3. How does the protocol, design, or system work?
  4. What are the key insights in the design that enabled it to advance the state of the art?
  5. How implemented and evaluated, what are the key results?
  6. What related problems are still open; is problem fully solved?

- Other 50% of your class participation grade

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Discussion Paper Presentations

- Each student presents 2-3 research papers over the semester
  - Papers are marked **Paper Discussion** on schedule

- Your talk should **clearly explain ideas** and **constructively critique** the ideas and results

- Lead presenters listed on schedule, **allocated** first-come, first-serve by **emailing instructor**

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Discussion Paper Presentations

- Chalk talk or slides for **30-45 minutes**
- Then, **open discussion**
  - Come prepared to **lead class discussion** after talk
    - Based on Perusall discussion, your own thoughts
  - Non-presenters should be prepared to actively participate in the discussion

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Outline of a Discussion Paper talk

- Motivation and problem statement (**context**)

- State main contributions of work (**core ideas**)

- → Description of central design
- → Experimental evaluation
- → Related and Future work
- → “Opinion part”
- → Summary of Perusall Discussion (on Perusall)

Talk: Description of central design

- Focus on the **most important points:**
  - Understanding **how and why the system**, design, or algorithm works
  - To **understanding results** in the experimental evaluation

- **Clarity,** not “parroting,” is very important here:
  - Often, describe in a **top-down fashion**
  - Start with the **overall design** of the proposed work
  - Identify parts of the solution, then identifying the sub-parts of those parts, *et cetera*

Talk: Experimental evaluation

- **What questions** do the authors ask in their evaluation?
  - What is the authors' hypothesis for each question and why?

- Does evaluation **stress the system** to its **"breaking point?"**
  - Multiple axes? **Transparency** of system's **limitations**

- What **baselines** for evaluation? Are they **fair**? Any **missing**?

- For any **graph** you show or refer to:
  - First, **explain axes and trend:** why behaves as it does
  - **Justify:** refer to design, experimental details
  - Anything seem **anomalous**? Note and try to explain

Talk: Related and future work

- What are the **most closely related** other systems/results?
  - How are they **similar, different**? Significant differences?
- Should read citations enough to understand differences
- Should search for related work published after/with the paper
- **No need to claim** the work you are presenting is **"better" or "worse"** than a particular piece of related work
  - Often it is simply that the two pieces of work are different
- But, should **articulate the precise difference** (*e.g.*, "this work solves a slightly different problem…")

Talk: Opinion part

- Offer **your final critical assessment:**

1. What are the **strengths** of the work?
2. What are the **weaknesses/limitations**?
3. What important questions are left **unanswered**?

Talk: Summary of Perusall Discussion

- Suggest you **open** up the paper **in Perusall** web page
- **Drill down** into the most insightful discussion threads
- Summarize out loud, then **we discuss as a group**

Independent Research Project

- **Systems-building,** involving significant programming effort
  - "*We believe in rough consensus and **running code***"

- Two options:

1. **Reimplementing and Reproducing Research Project**
   - Independently reimplement a 597E paper
   - Reproduce the results

2. **Novel Research Project**
   - Must be closely related to 597E
   - Must be formulated in consultation with instructor

Project: What and When

- Systems-building project involving significant programming
  - **Individually, or in small teams**
  - **Working code** uploaded to github and shared with instructor

- **Timeline:**
  - 9/23: Team Formation and Initial Project Proposal deadline (500-750 words, on **Ed Discussions**)
  - 9/23–10/23: Proposal Discussion Period (**Ed**)
  - 10/23: **Final Project Proposal deadline**
  - 12/12 (Dean's Date) 11:59 PM: **Final Project Report** and Source Code Submission deadline

Project Proposal: Reproducing Research

- **Structure:**
  - Background paragraph of the paper, authors, venue
  - Summarize problem domain and challenges
  - Describe design, evaluation, key experimental results
  - Present **reproduction and evaluation plan** (biggest part)
    - Implementation strategy (language, framework)
    - Evaluation strategy (experiment design, data sources)
    - Which key results will you reproduce?

- If in a team: provide work plan, including rough division of labor

Project Proposal: Novel Research

- Novel Research Proposal
  - *Introduce and clearly explain* the problem
    - context: most relevant related work with citations
  - Sketch high-level system design (changeable!)
  - Highlighting new knowledge contributions
- If applicable, provide a plan for experimental evaluation (changeable!)
- If in a team: provide work plan, including rough division of labor

Project: Final Report

- Same structure as the research papers we will read:

- Introduce and motivate the problem
  - Placing in context of some related work

- Describe your design clearly

- Present a performance evaluation
  - Comparing your design to a “strawman” system

- More related work, and conclusion

Seminar Grading

- **30% participation**, of which:
  - 50% online E-Discussion (Perusall) participation
  - 50% in-person participation

- **30% oral presentations**, of which:
  - 50% discussion research paper presentations
  - 50% research project presentation

- **40% research project**, of which:
  - 15% proposal
  - 25% project status report, demo, code/design walkthru
  - 60% final written report and code

Next Time: NERF2