NeWRF: A Deep Learning Framework for Wireless Radiation Field Reconstruction and Channel Prediction

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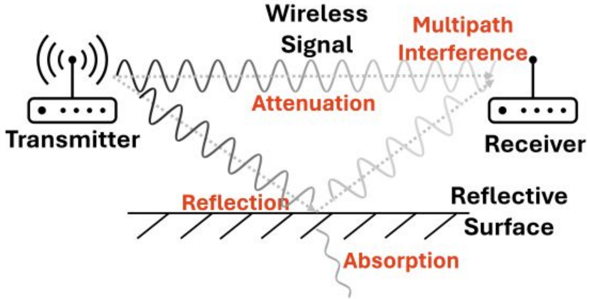
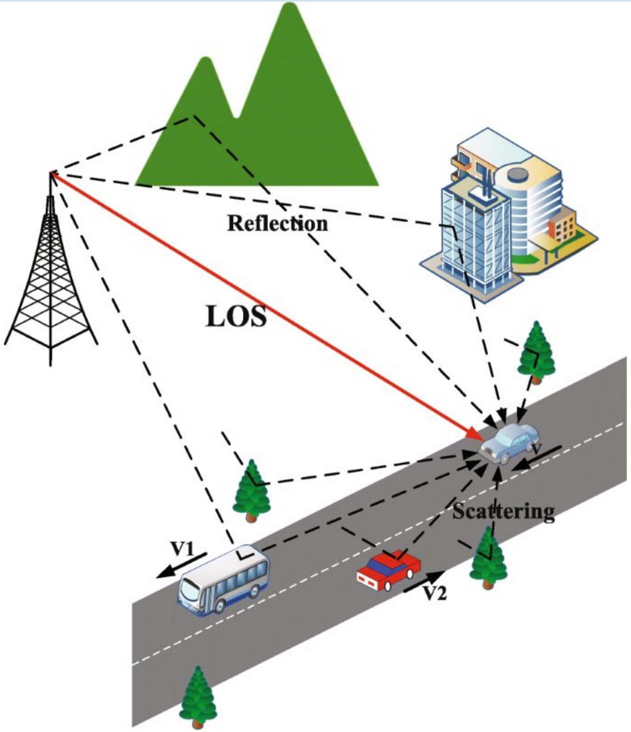
The Channel Prediction Problem

What is the wireless channel?

$$h = \frac{y}{x} = \sum_{l=0}^{L-1} A_{att}^{l} e^{j\Delta\psi^{l}}$$

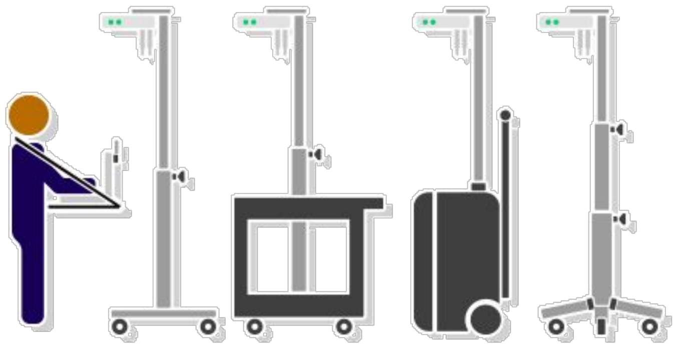
- Attenuation
- Phase Rotation
- Multipath Interference





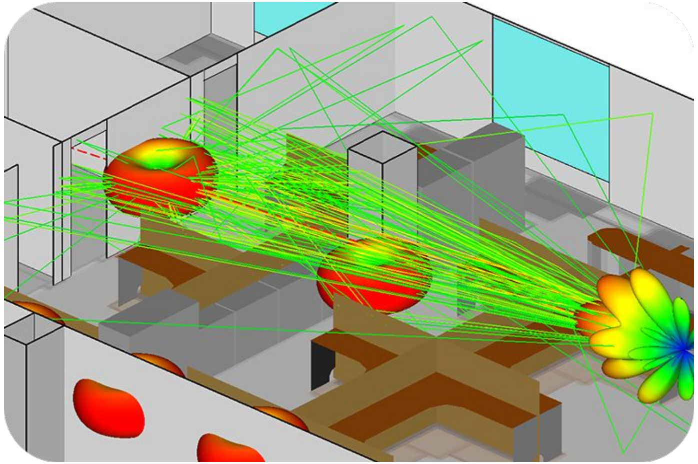
Approaches for Channel Prediction

Site Surveys:



- Expensive (Time and cost)
- Dead spots that aren't visited missed

Ray Tracing Simulations:



- Requires CAD models of environment
- Still requires supplemental site surveys

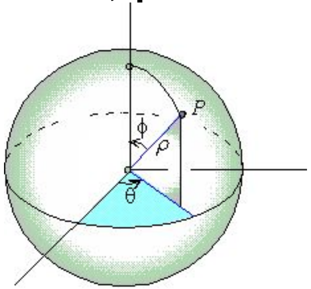
NeWRF

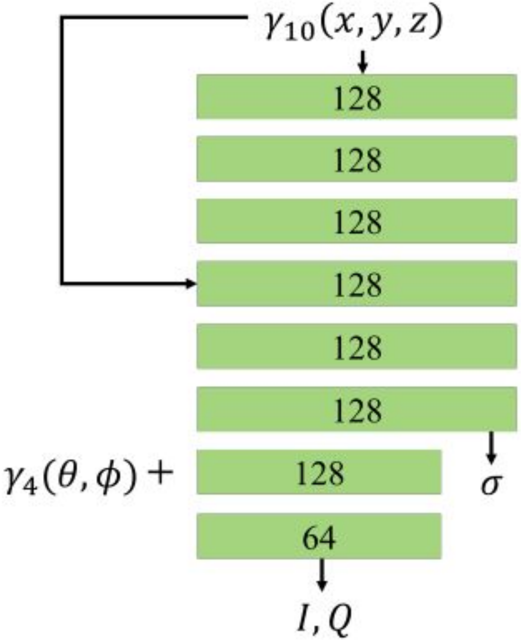
Deep learning for Wireless Radiance Field Reconstruction

The authors' proposed framework:

- Eliminates the need for CAD models in channel prediction
- Requires a smaller measurement density than previous deep learning approaches
- Incorporates the physics of attenuation, phase rotation, and reflection

Neural net maps (x,y,z,θ, ϕ) -> (A, ψ, σ) (Amplitude, phase, volume density)



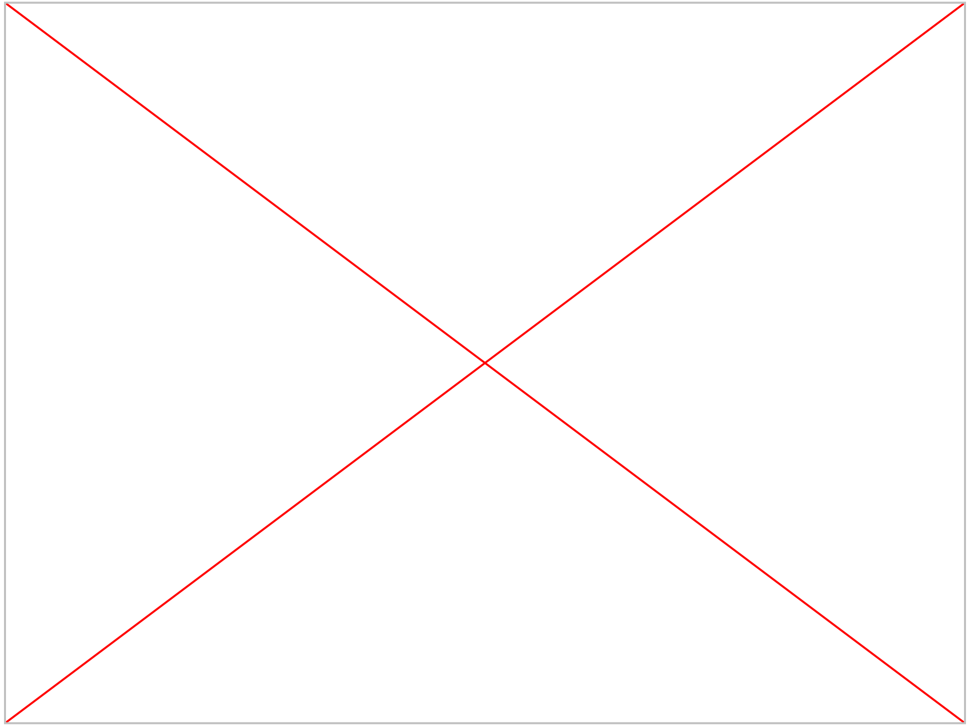


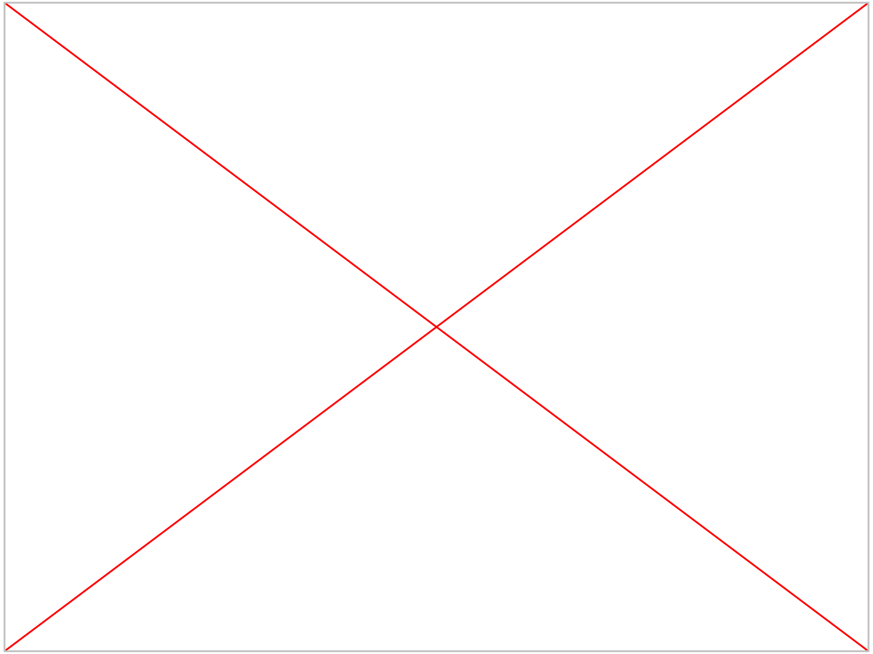
NeRF or Nothing

NeWRF Builds on NeRF (Neural Radiance Fields)
NeRF:

- Learns a continuous radiance field function of a 3D Scene from 2D images of that scene using a deep neural network (MLP)
- MLP Maps $(x, y, z, \theta, \phi) \rightarrow (r, g, b, \sigma)$: Camera ray angle relative to a point in 3D-Space → Radiance of red, blue, and green light + volume density at location
- Can generate new, realistic images of the scene from any viewpoint
- Incorporates physics of light propagation

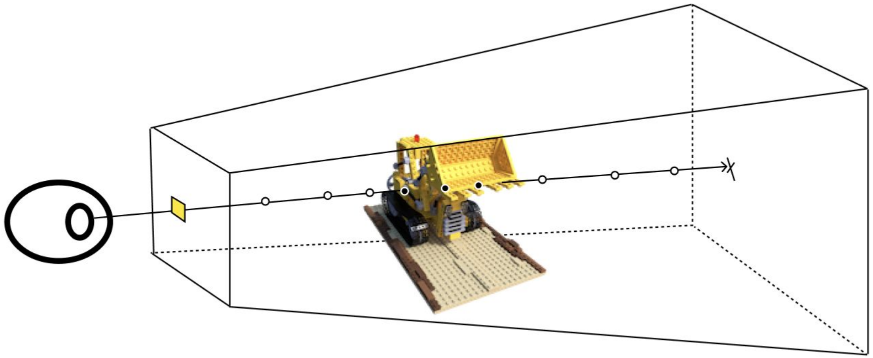
NeRF Examples





Ray Tracing + Volume Rendering

To generate images from a viewpoint, NeRF:
Uses ray-tracing:



Uses volume rendering with samples along each ray:
Approximately integrates volume density σ(x) to find the expected color of a camera ray

$$C(\mathbf{r}) = \int_{t_n}^{t_f} T(t)\sigma(\mathbf{r}(t))\mathbf{c}(\mathbf{r}(t), \mathbf{d})dt \,, \text{ where } T(t) = \exp\left(-\int_{t_n}^{t} \sigma(\mathbf{r}(s))ds\right)$$

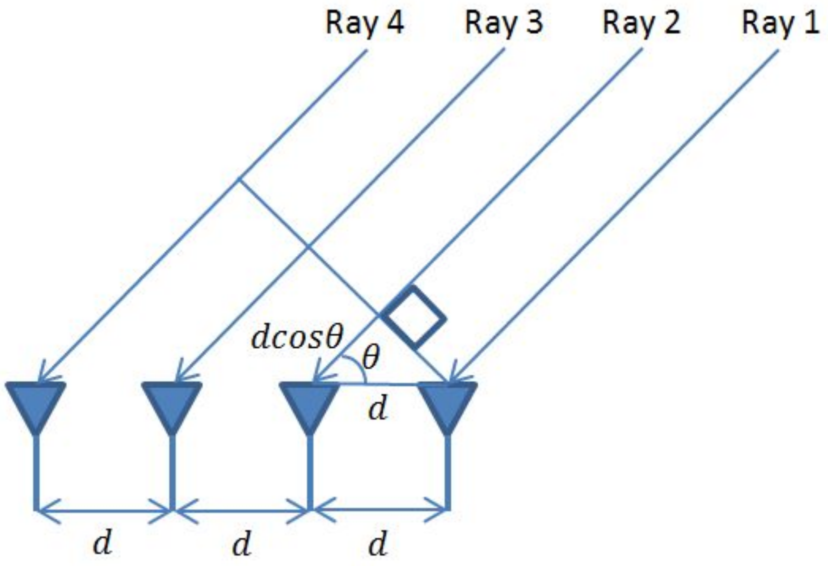
Radiance Field to Wireless Field

Unlike Radiance Fields, Wireless Fields:

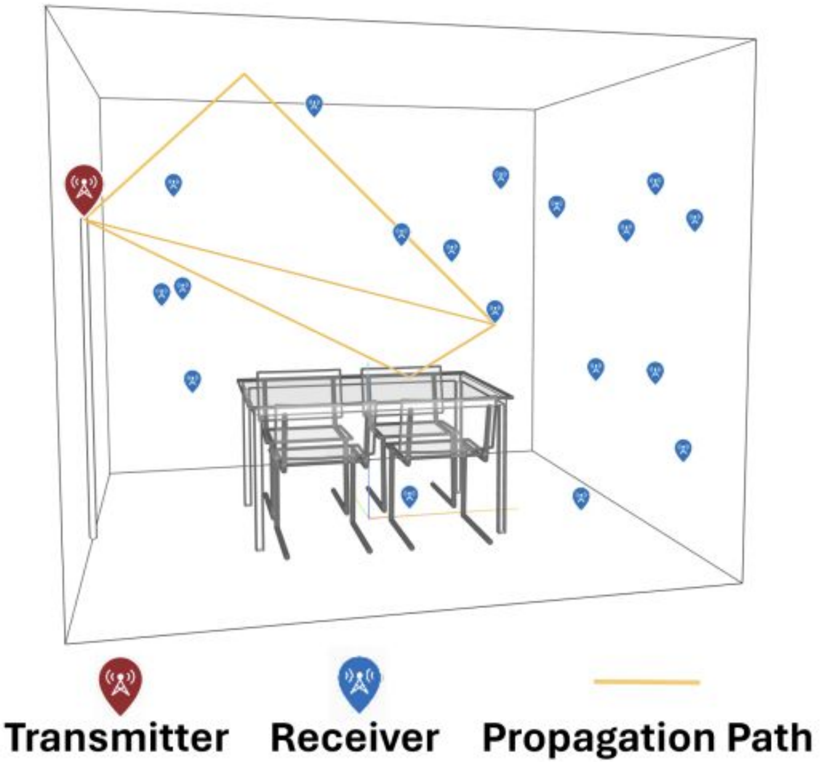
- Span environments larger and more complicated than NeRF scenes
- Measure a single complex number at each point vs thousands of pixels (R,G,B)
- Are Measured from antennas, which capture signals in every direction vs one direction of an image sensor
- Propagate in more complex ways than visible light due to longer wavelengths

To handle this, rather than sampling all ray angles (360*180), authors assume Direction-of-Arrival (DoA) of 10-20 most significant rays is known a priori

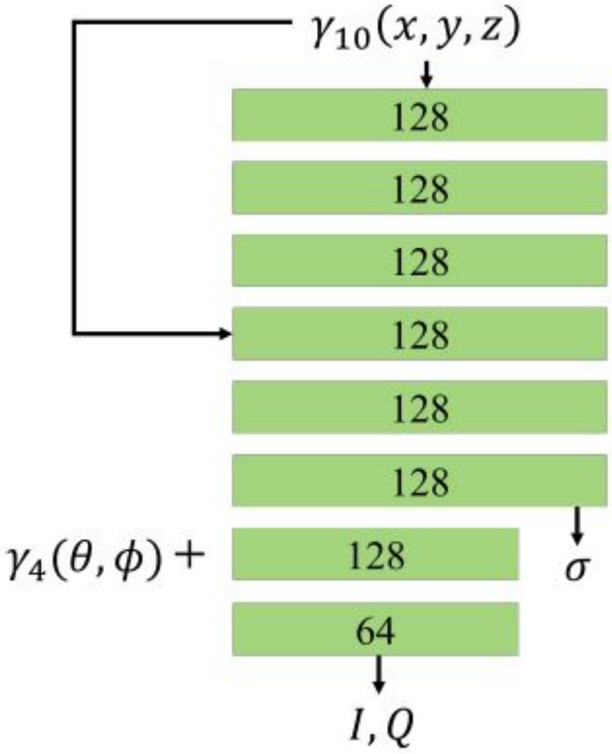
Direction of Arrival (DoA) Prior



Phase differences across antenna array



NeWRF Architecture

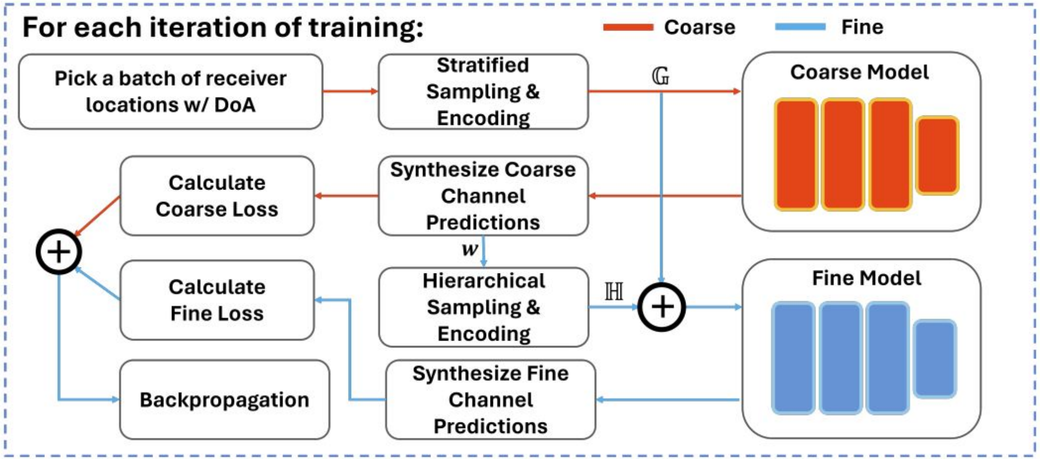


- Multilayer perceptron, 5->3
- Fine and Coarse Model with same (left) architecture

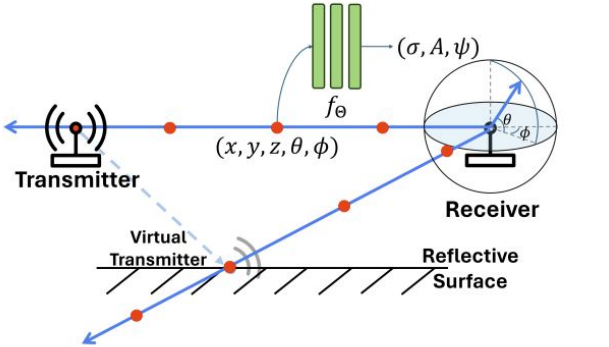
Training NeWRF

To train NeWRF the authors:

- Simultaneously train a coarse and fine model with mini-batch GD
- Use the ray-sampling technique to approximate the channel from known DoAs, similarly to color integral of NeRF
- High weight coarse samples used to densely sample regions for fine model
- Compare sampled channel to ground truth channel with Loss Function



$$H(f) = \sum_{\mathbf{r}\in\mathbb{L}} \sum_{\mathbf{p}\in\mathbb{P}} w_{\mathbf{rp}} A_{\mathbf{rp}} \frac{c}{4\pi d_{\mathbf{p}} f} e^{j(\psi_{\mathbf{rp}} - 2\pi f d_{\mathbf{p}}/c)}$$



(I, Q) vs (A, ψ) + NMSE

The authors configure the model to directly predict real and imaginary components of channel vs amplitude and phase, why?

Phase is mod 2π, modulo is not differentiable and the model uses gradient descent.

The authors use a Normalized Mean Square Error (NMSE) for training, why?

$$L(\mathbf{h}, \hat{\mathbf{h}}) = \frac{\sum |\hat{\mathbf{h}} - \mathbf{h}|^2}{\sum |\mathbf{h}|^2}$$

Channel is at scale 10e-1 ~ 10e-5 and varies by orders of magnitude in dataset, avoid vanishing gradients.

The Observed Wireless Scene

- The authors expected their model to assign high volume density to points described as “virtual transmitters”
- They modeled these “VTx” as lying on reflective surfaces at points of incidence
- In reality, the model learned a representation of the scene that placed VTx at virtual images

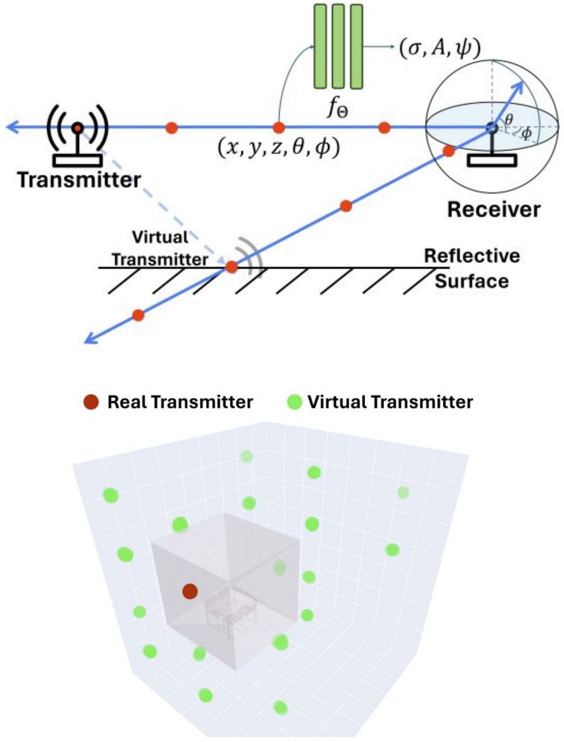
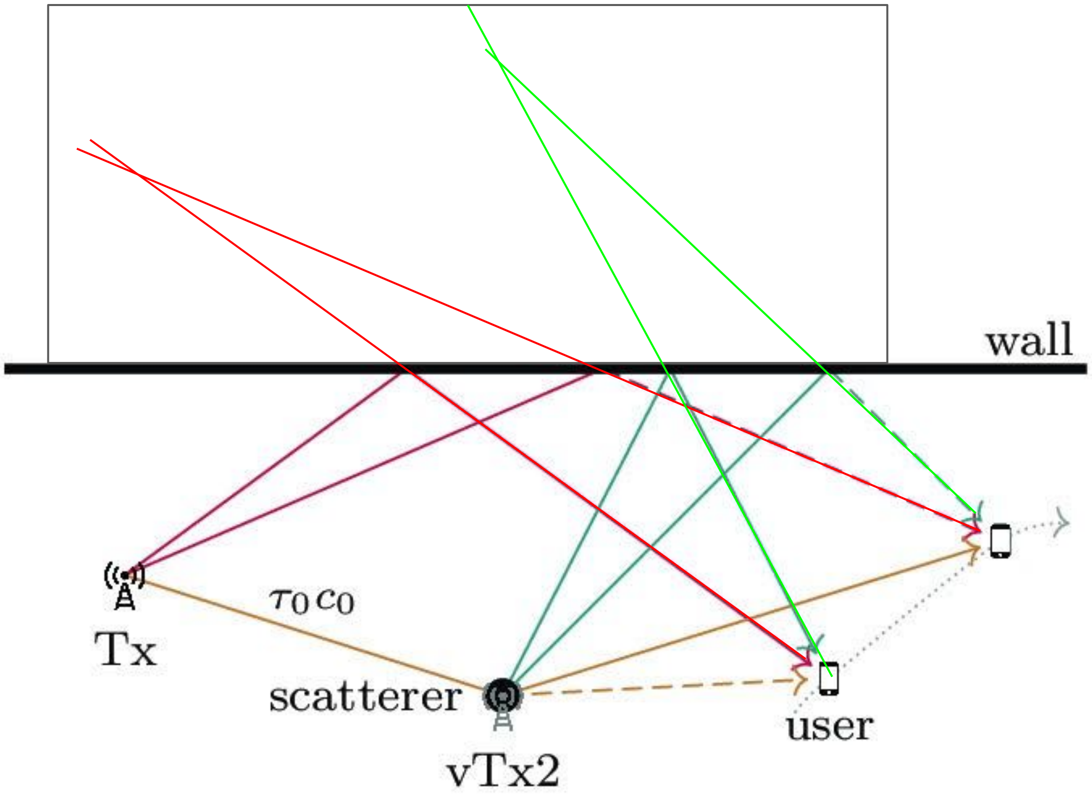
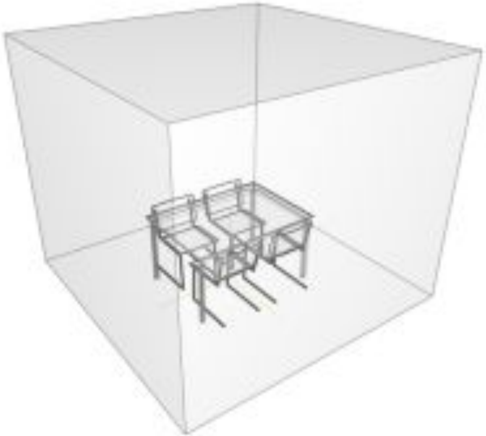


Figure 5. **A Learnt Wireless Scene:** Spots with high volume density values indicate the locations of (virtual) transmitters. The gray cube shows the 3D environment model presented in Figure 3.

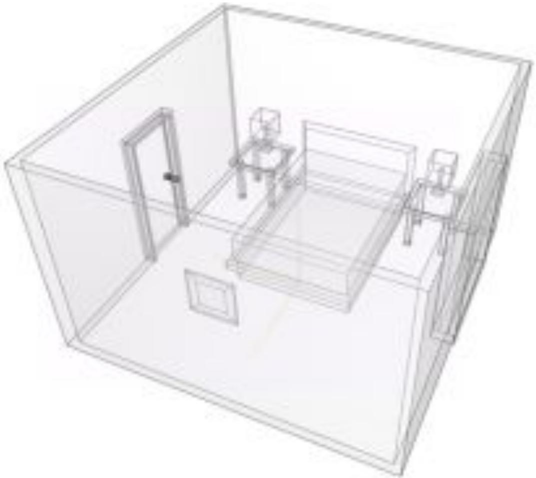
Find the Virtual Transmitters



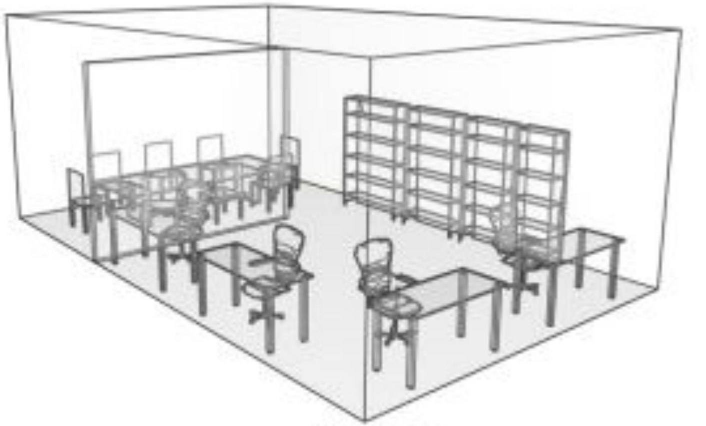
Simulated Environment Models



Conference Room
$(9.8ft \times 9.8ft \times 8.2ft)$



Bedroom
$(16.4ft \times 15.7ft \times 9.8ft)$



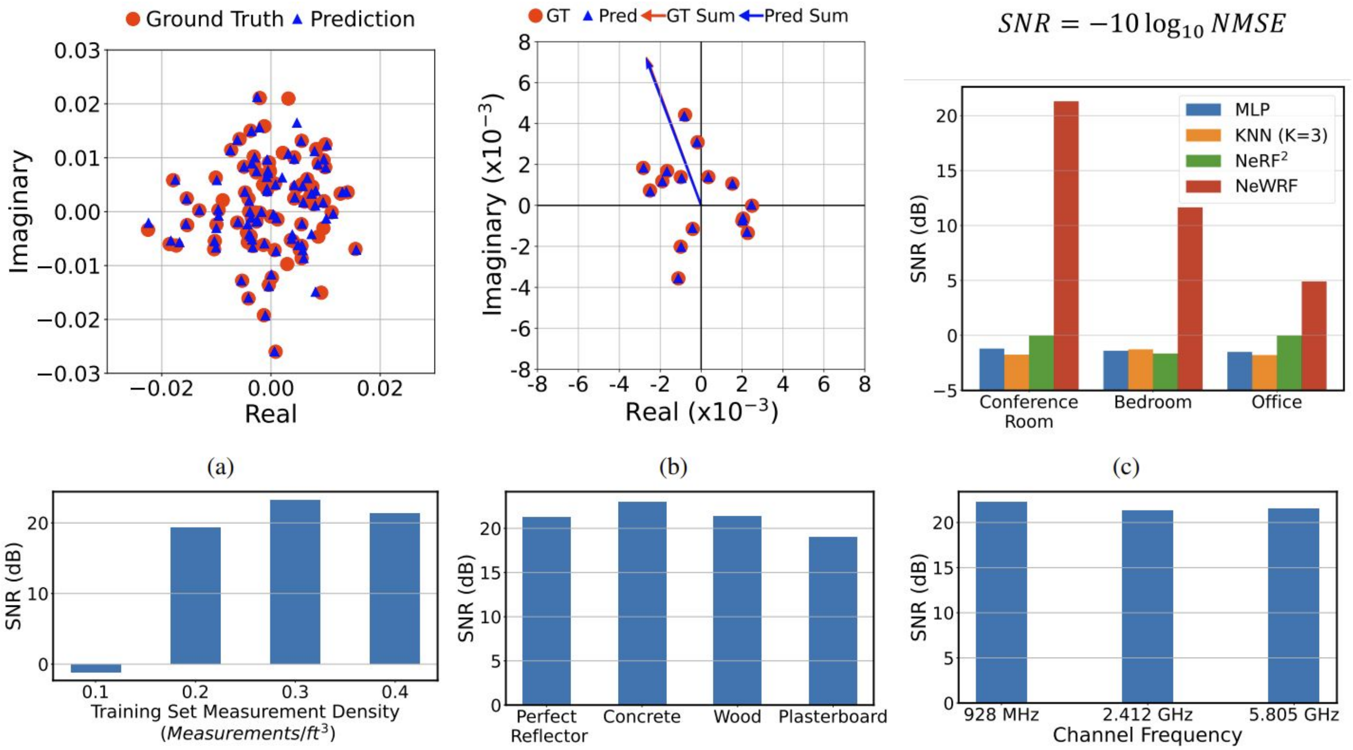
Office
$(26.2ft \times 16.4ft \times 9.8ft)$

Ray-Searching

For NeWRF Testing Performance i.e. Inference at unknown locations, DoA Information is not available, so the authors created an algorithm to search for arrival rays based on the training data:

1. **Intersection Point Identification:** ray march from training data to find a set of VTx
2. **Refine (Virtual) Transmitters:** Cluster set from 1 to yield reduced set of centroids
3. **(Virtual) Transmitter Assignment:** Find closest VTx on each DoA for every receiver location in training set, combine in set
4. **(Virtual) Transmitter Count Estimation for Testing Locations:** Train neural network on 3 to map receiver locations to a **number** of VTx, use prediction for test location.
5. **Voting-based (Virtual) Transmitter Selection:** Use 6 nearest neighbors of test location in training set, assign VTx of neighbors to test location t

Results: Channel Prediction

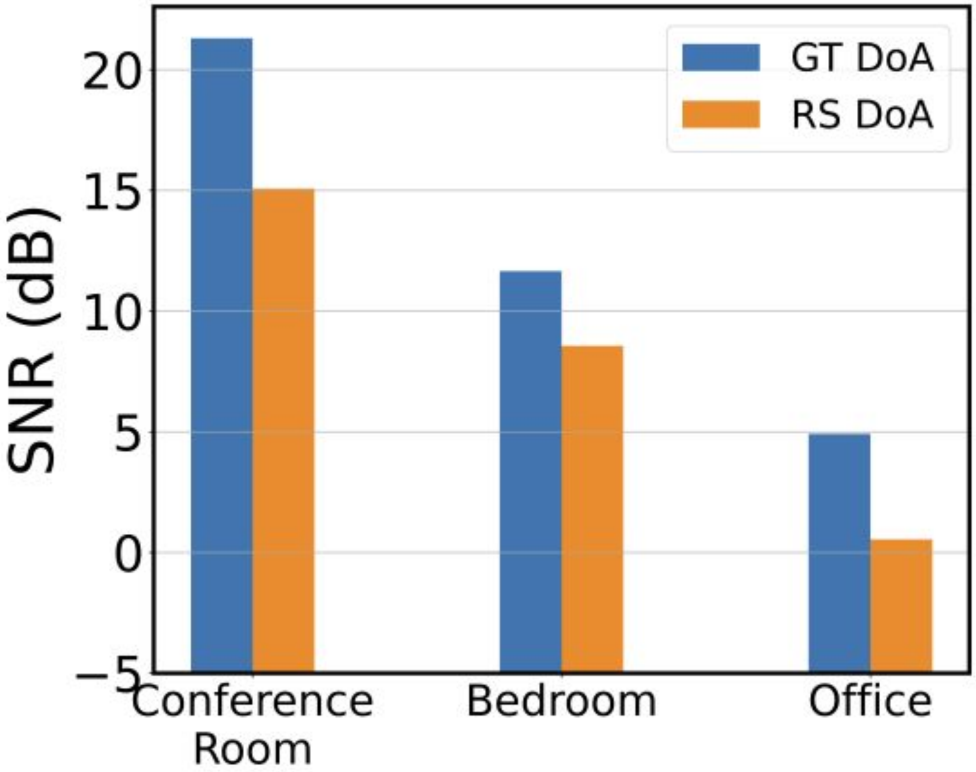


(a) (b) (c) (d) (e) (f)

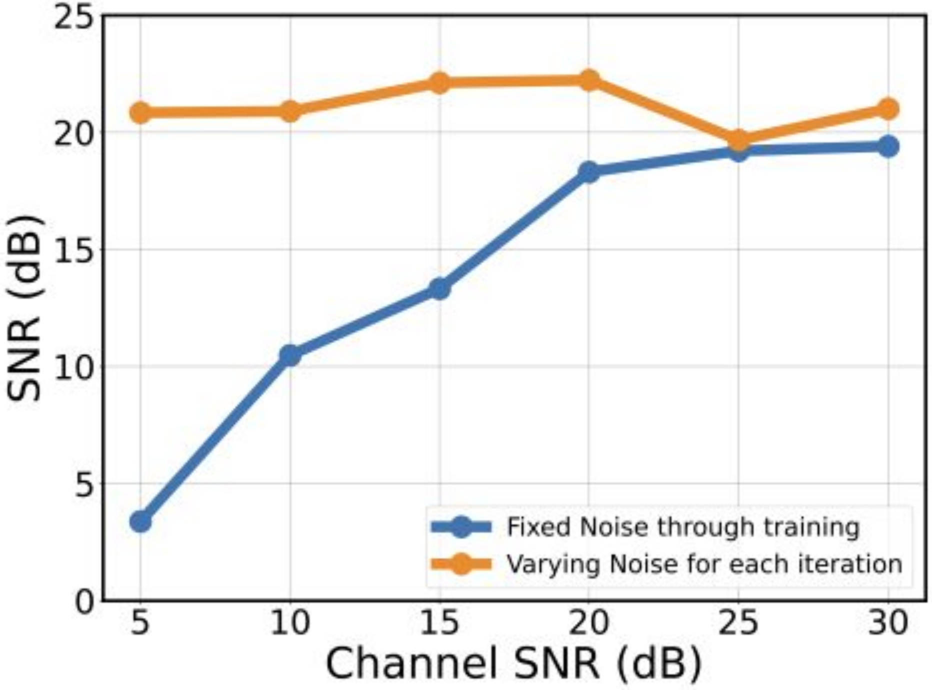
Competing Benchmarks:

- KNN
- NeRF^2 (moving transmitter)
- 7 linear layer MLP

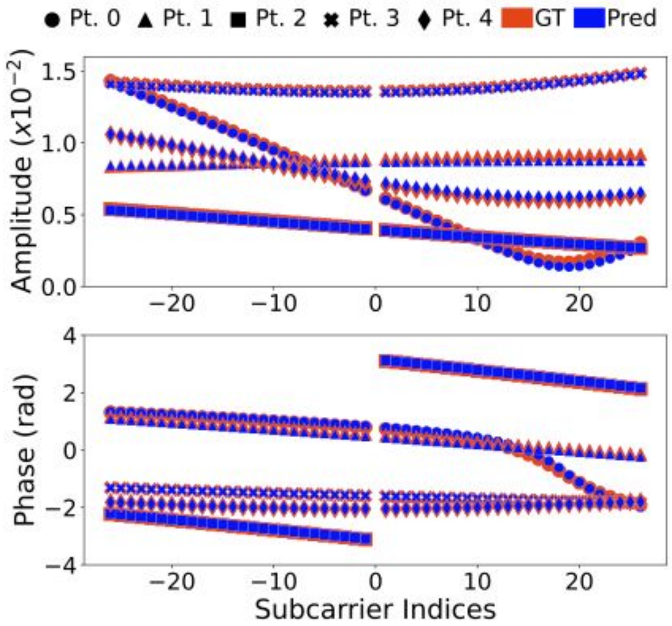
Results: Ray Searching

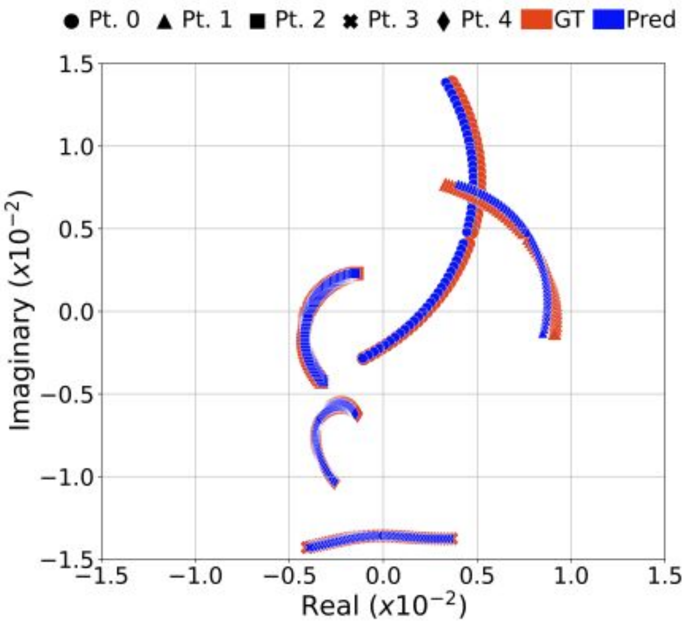


Results: Presence of AWGN



Results: Subcarrier Channel Prediction





Wifi, 5G subcarriers are each different channels. NeWRF Performs well w/o Fine-Tuning against Ground Truth

Discussion

Where are the Real World Results?

- No case studies using real world measurements

Is a DoA Prior Realistic in Practice?

Smartphone DoA Angular Resolution Capabilities, Bluetooth and Wifi:

- 5° typical with 4-antenna arrays, 2° with dedicated AoA hardware

Low resolution would require more rays to be traced + sampled, hurting performance

Are You Convinced by NeWRF?

Do you think NeRF would be effective:

- In a classroom like this one?
- In a larger indoor space (lecture hall)?
- Outdoors?