Physics-Unrolled Neural Operator for Accelerating High-Fidelity Wireless Ray Tracing

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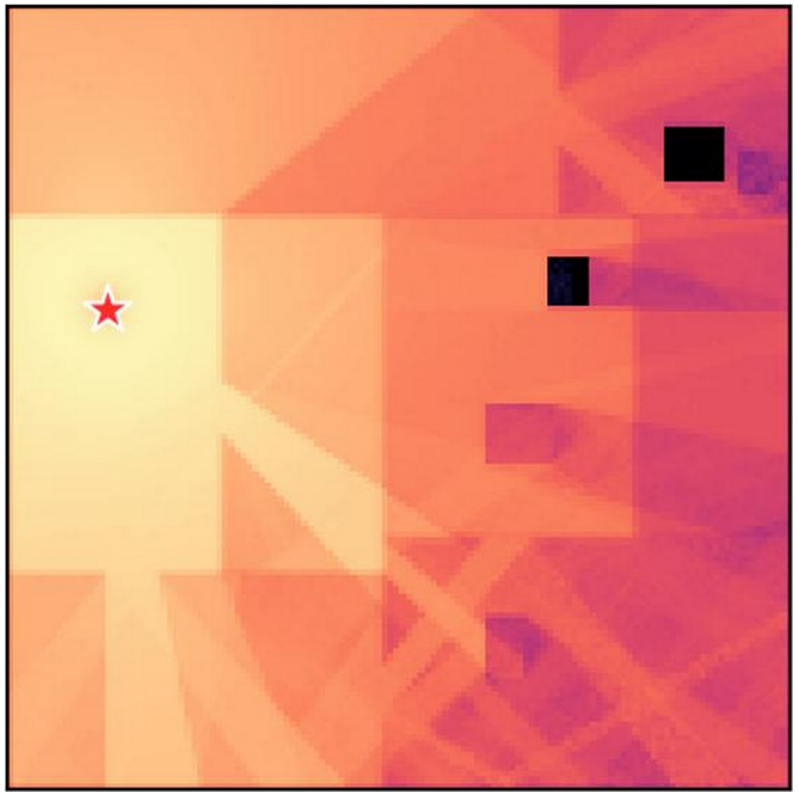
The problem: where should the access point go?



Floorplan. The positions marked ? are illustrative.

ray tracer

about 28 s

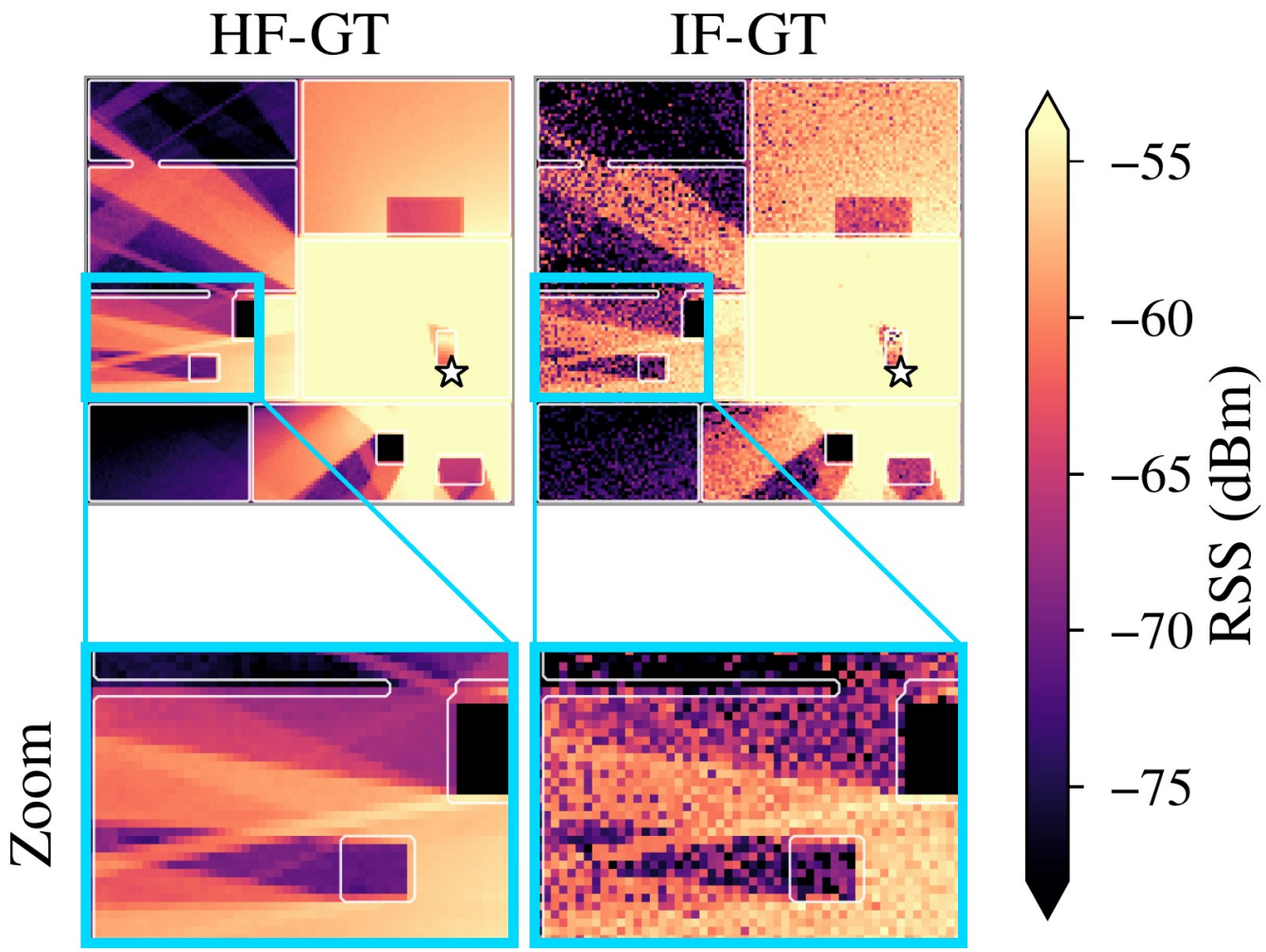


Radio map for the position marked Tx (lighter: stronger signal)

About 28 s
for one high-fidelity radio map

Thousands
of maps to plan a single building

The difficulty: the affordable labels are noisy

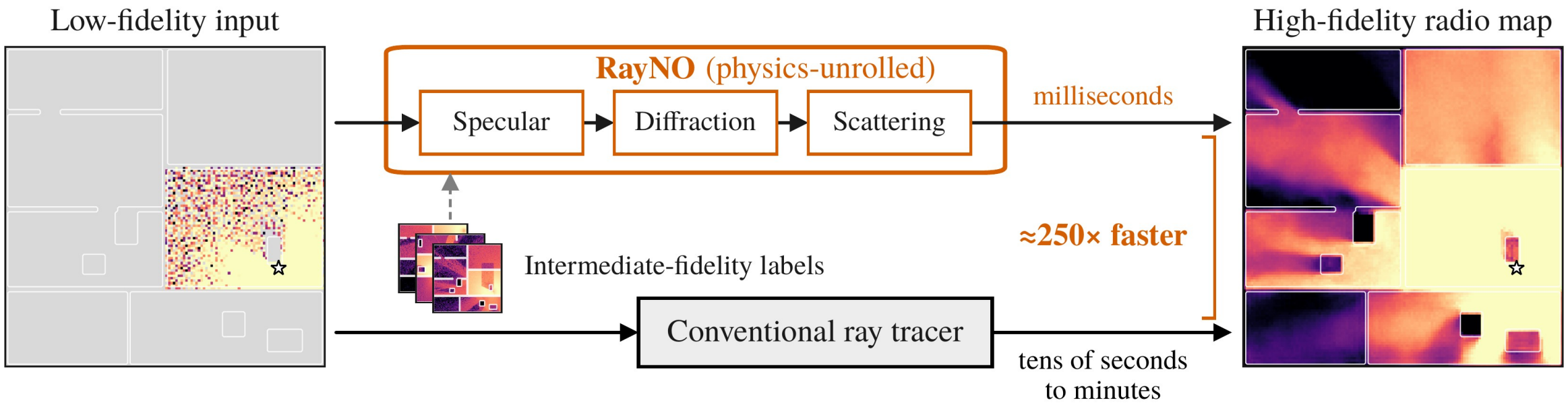


HF-GT (left): 10^8 rays. Used only for evaluation.

IF-GT (right): 10^6 rays. Used as the training label.

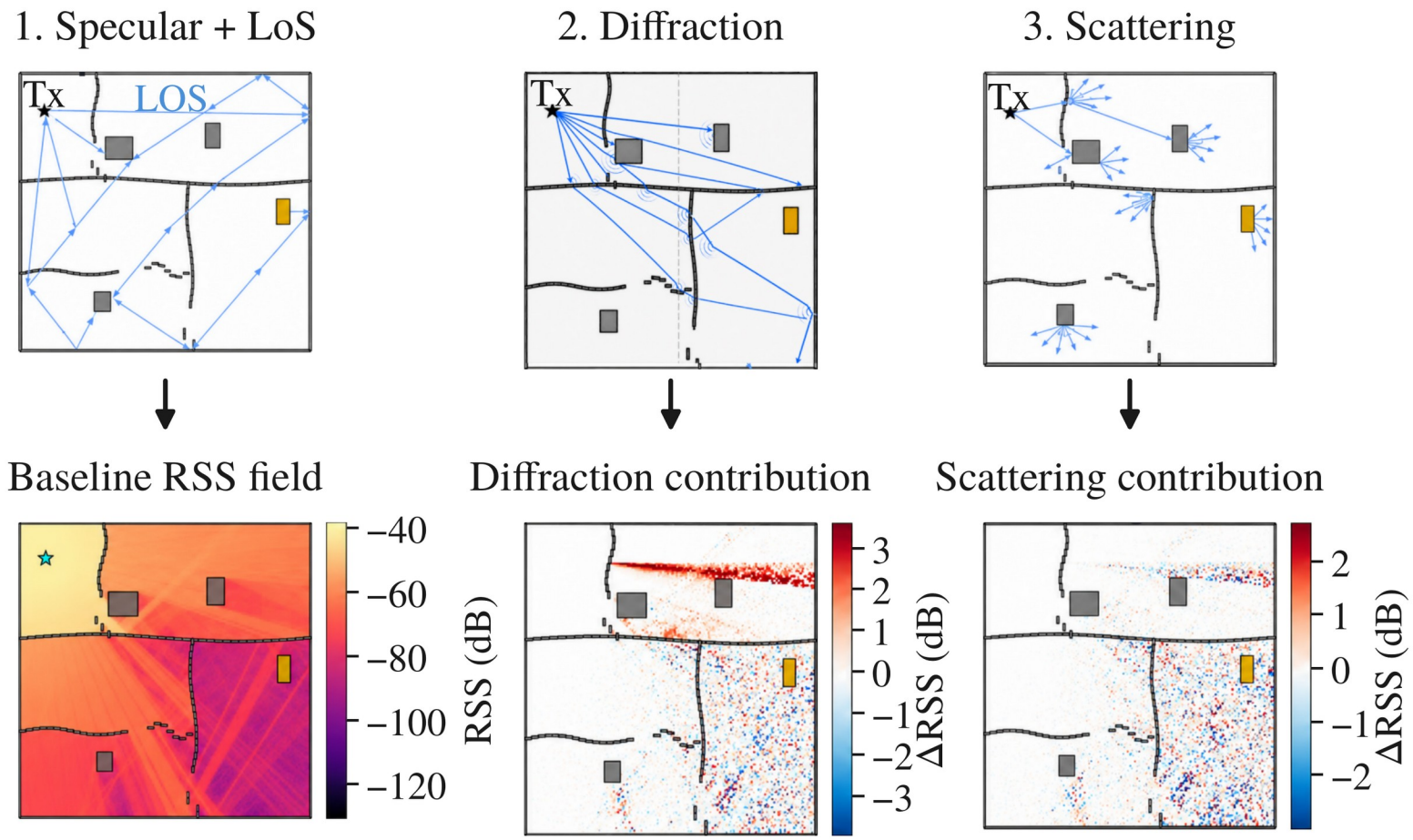
The label carries residual Monte Carlo noise.

RayNO: from one low-fidelity run to a high-fidelity radio map



About 0.11 s per map, including the low-fidelity run, against about 28 s for a high-fidelity simulation.

Three stages, one for each propagation effect



Stage 1, specular: broad coverage pattern.

Stage 2, diffraction: sharp changes near shadow boundaries.

Stage 3, scattering: fine local fluctuations.

Each stage is supervised by a label of matching physical complexity.

The assumption: conditionally unbiased label error

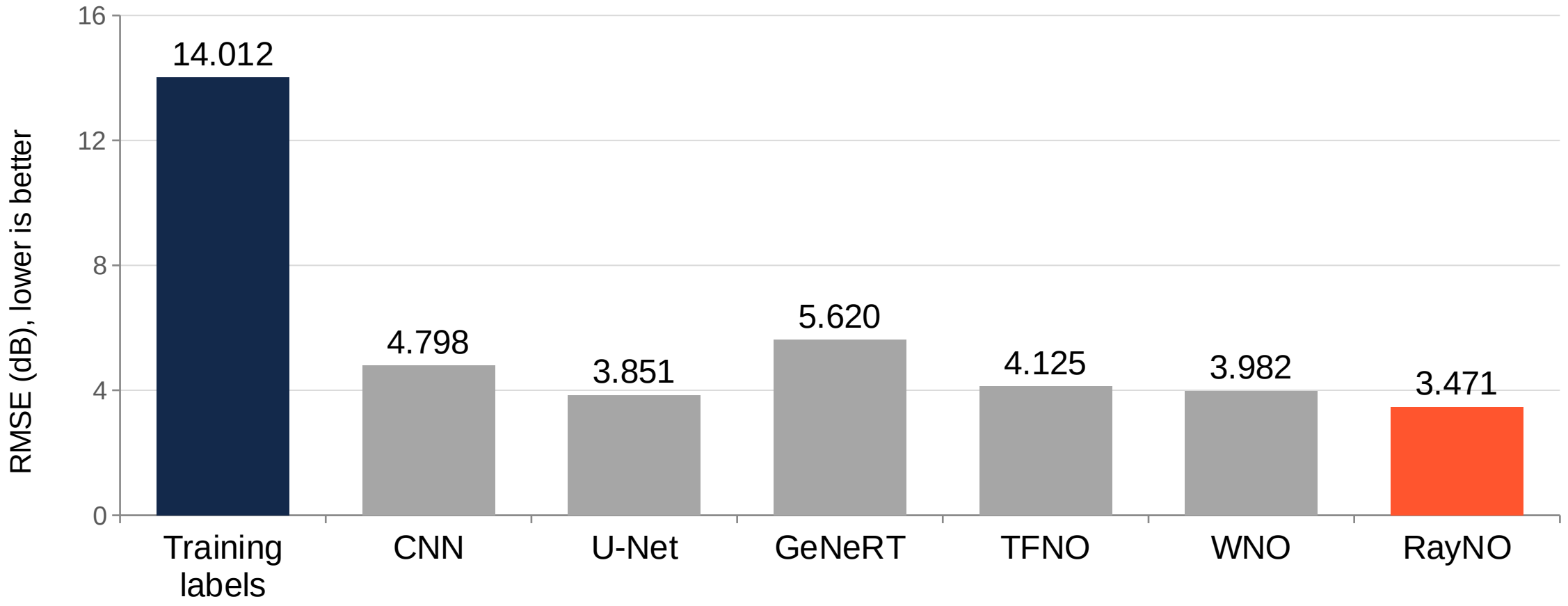
$$Y^{(i)}_{\text{IF-GT}} = Y^{(i)}_{\text{oracle}} + \varepsilon_i, \qquad \mathbb{E}[\varepsilon_i \mid X_i] = 0.$$

For a fixed scene, the label noise has zero mean, so it averages out across training scenes.

Simulator check, 512 independent seeds: averaging-error slopes between −0.493 and −0.502 (unbiased estimator: −0.5).

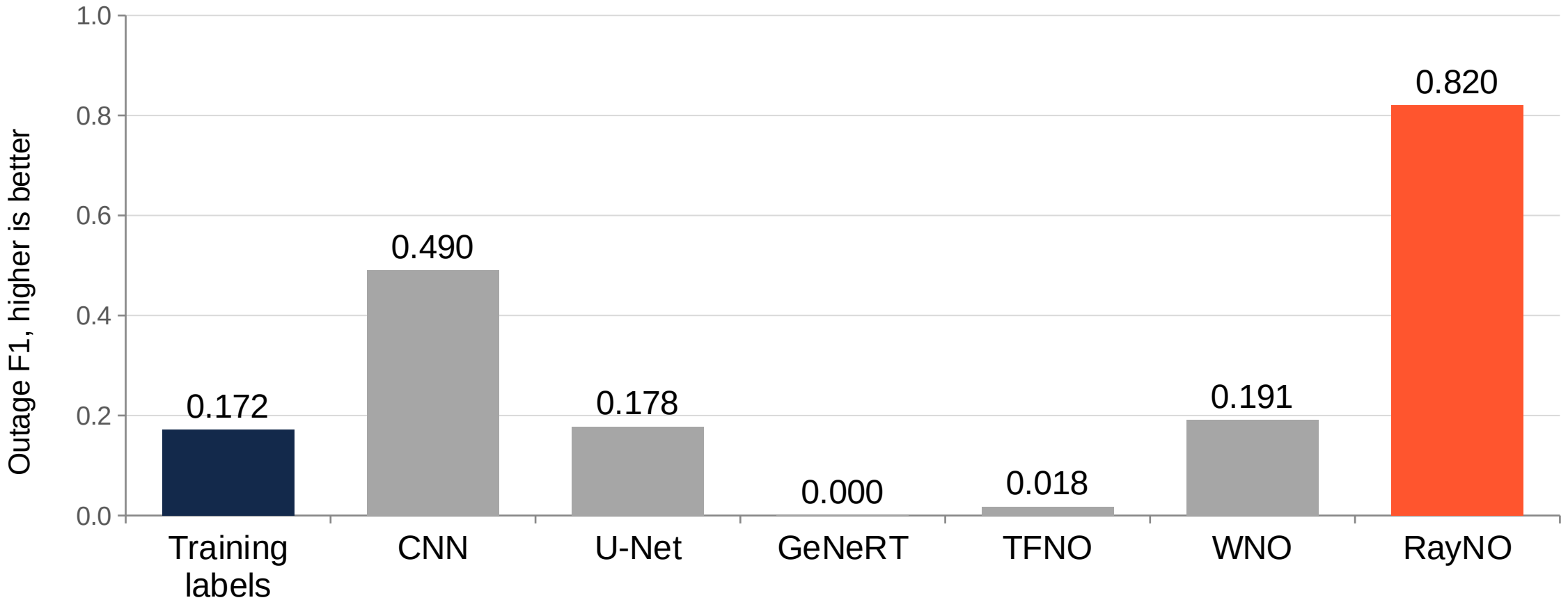
With biased label noise the model fails: RMSE 12.06 dB, Outage F1 0.359.

Image-quality metric: RMSE against the HF-GT reference



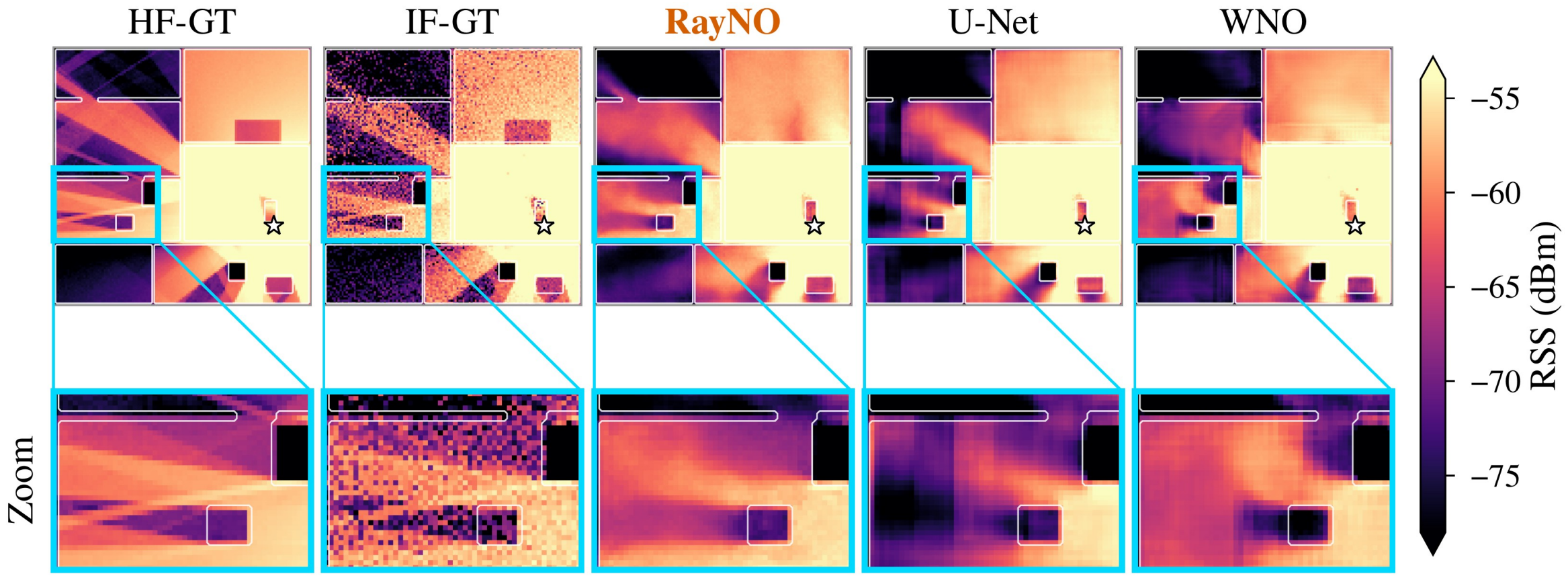
Five of the 13 baselines are shown. Most baselines also improve on the training labels.

Wireless metric: Outage F1 against the HF-GT reference



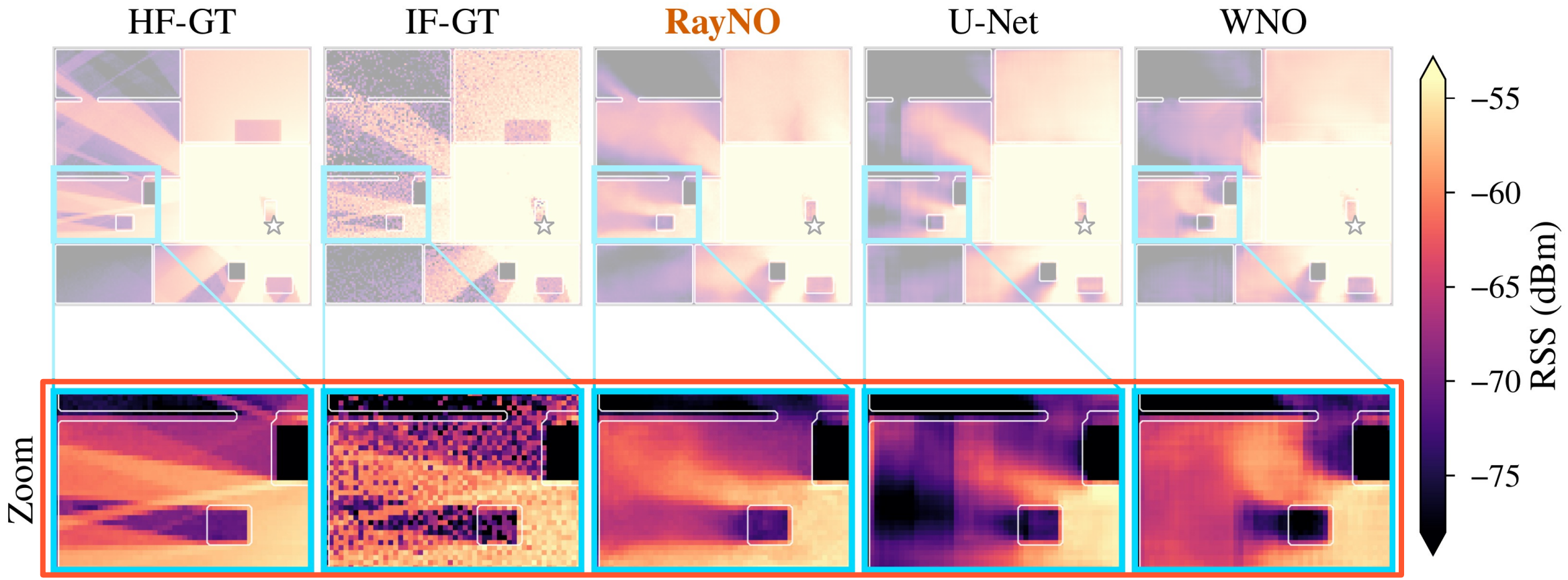
Illustrative access-point calculation: cell-edge throughput 92.0 Mbps for RayNO, 16.6 Mbps for CNN.

An example on a test floorplan



Walls are drawn in white. The star marks the transmitter.

The enlarged region



U-Net: blocky artifacts. WNO: blurred streaks.

Limitations

- All supervision and evaluation are based on ray tracing. No measured data.
- Indoor floorplans, 15 m × 15 m.
- Single frequency (5.5 GHz), single transmitter.
- Received signal strength only. No phase.
- Depends on accurate geometry and material priors.

Summary

Imperfect simulation labels can still support high-fidelity radio map prediction, when the label error is conditionally unbiased and the model is aligned with the propagation physics.

Thank you.

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