Foundation Models for Wireless Communication and Sensing: Learning Universal Representations with LWMs

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Joint work with my students:
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This work was supported in part by NSF (Grants No. 2048021 and 2426906) and by InterDigital, Meta, and Remcom

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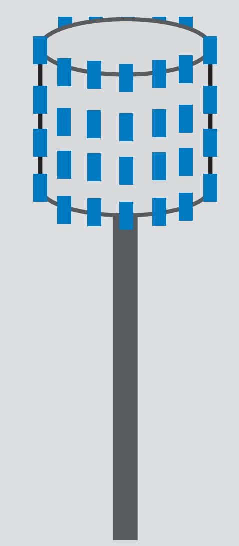
ARIZONA STATE UNIVERSITY

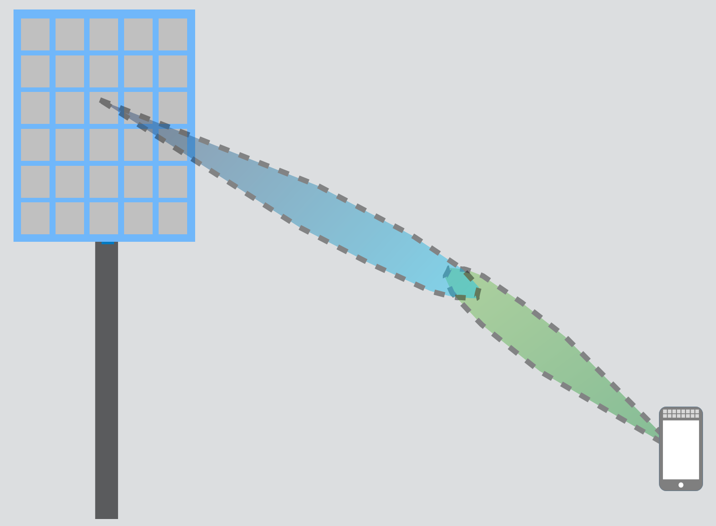
Wireless Intelligence Lab

Key trends in wireless communications and sensing

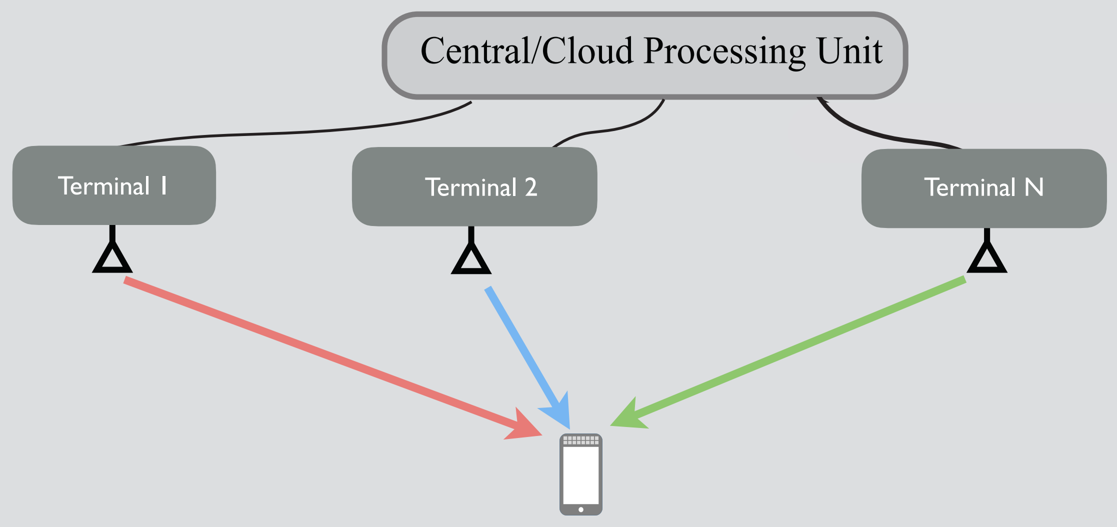
- The use of large antenna arrays (high spatial resolution)



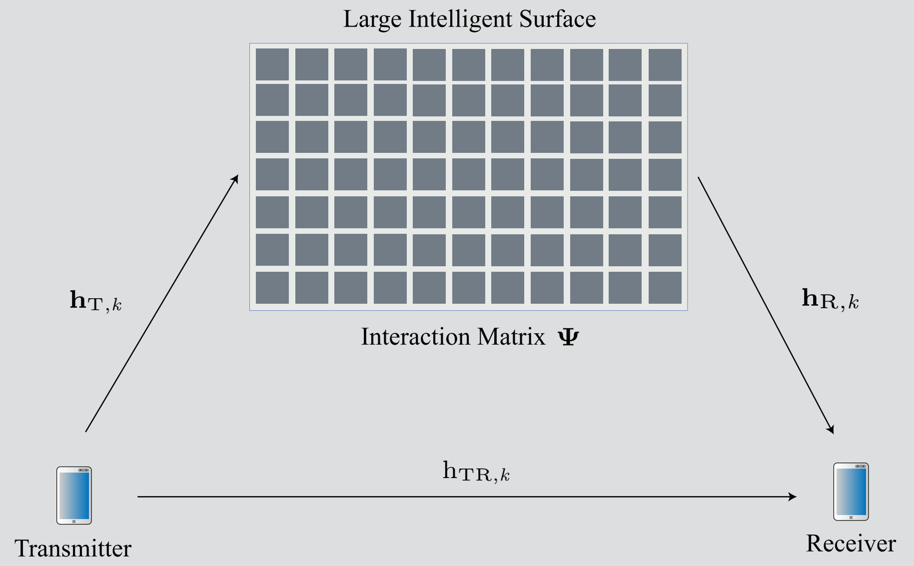
Massive MIMO



mmWave and THz MIMO



Cell-free massive MIMO



Intelligent Surfaces

- The increasing dependency on higher frequency bands (more bandwidth/range resolution)

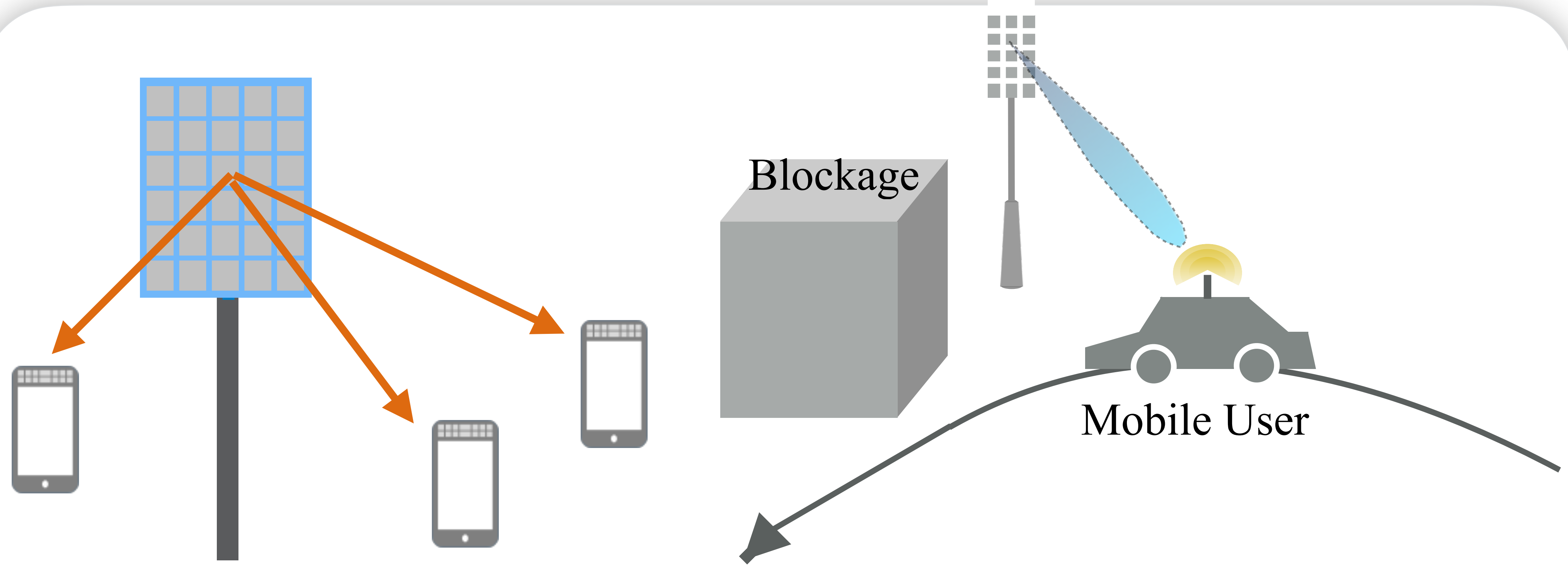
Sub-6GHz	Upper Mid-band	mmWave	sub-THz
	7-24 GHz	28-70 GHz	100-300 GHz
	6G	5G-6G	6G and beyond

Lead to higher data rates and better sensing capabilities

But … lead to other challenges!

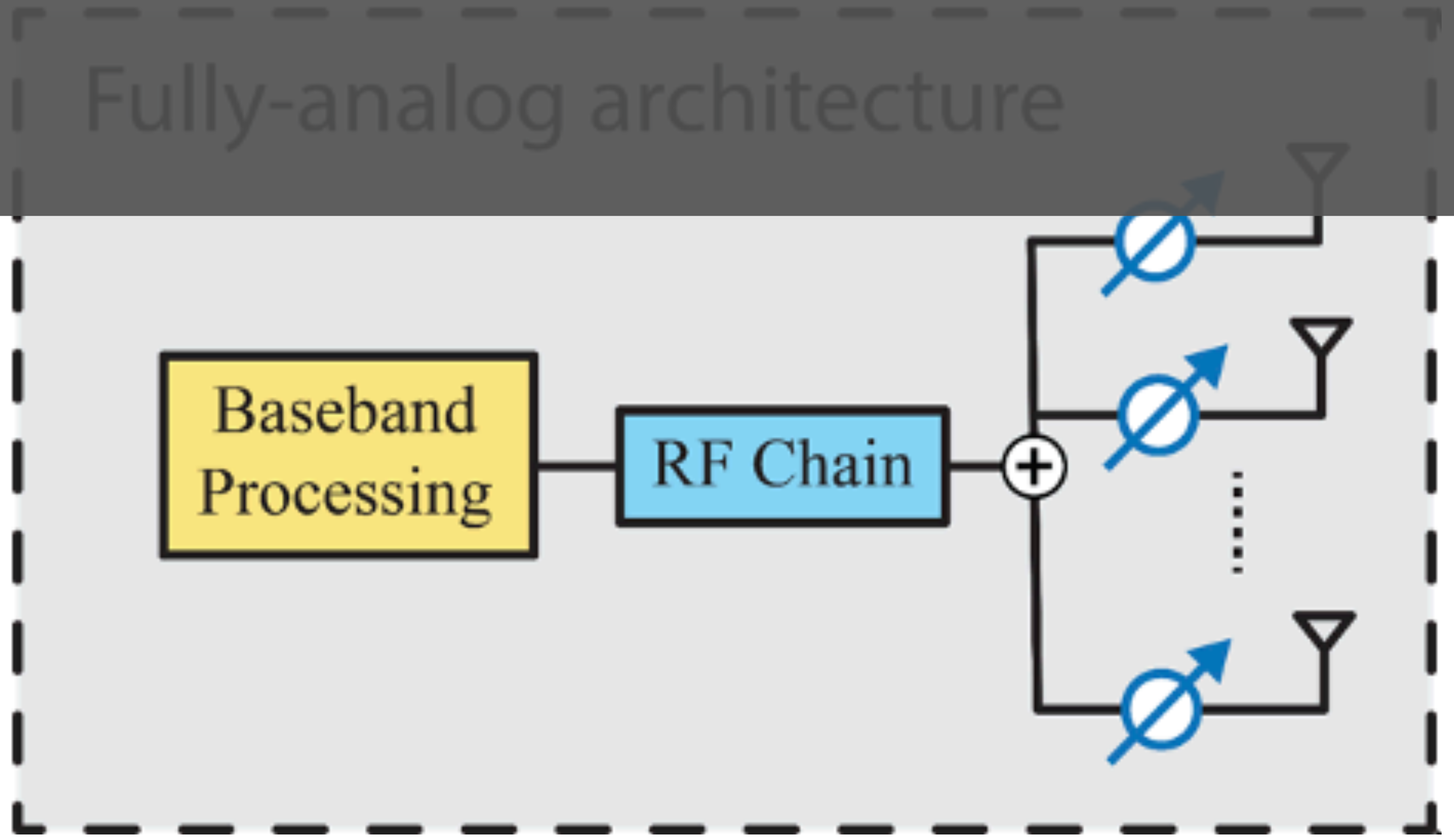
Challenges

Difficult to support mobility



Difficult to ensure robustness/reliability

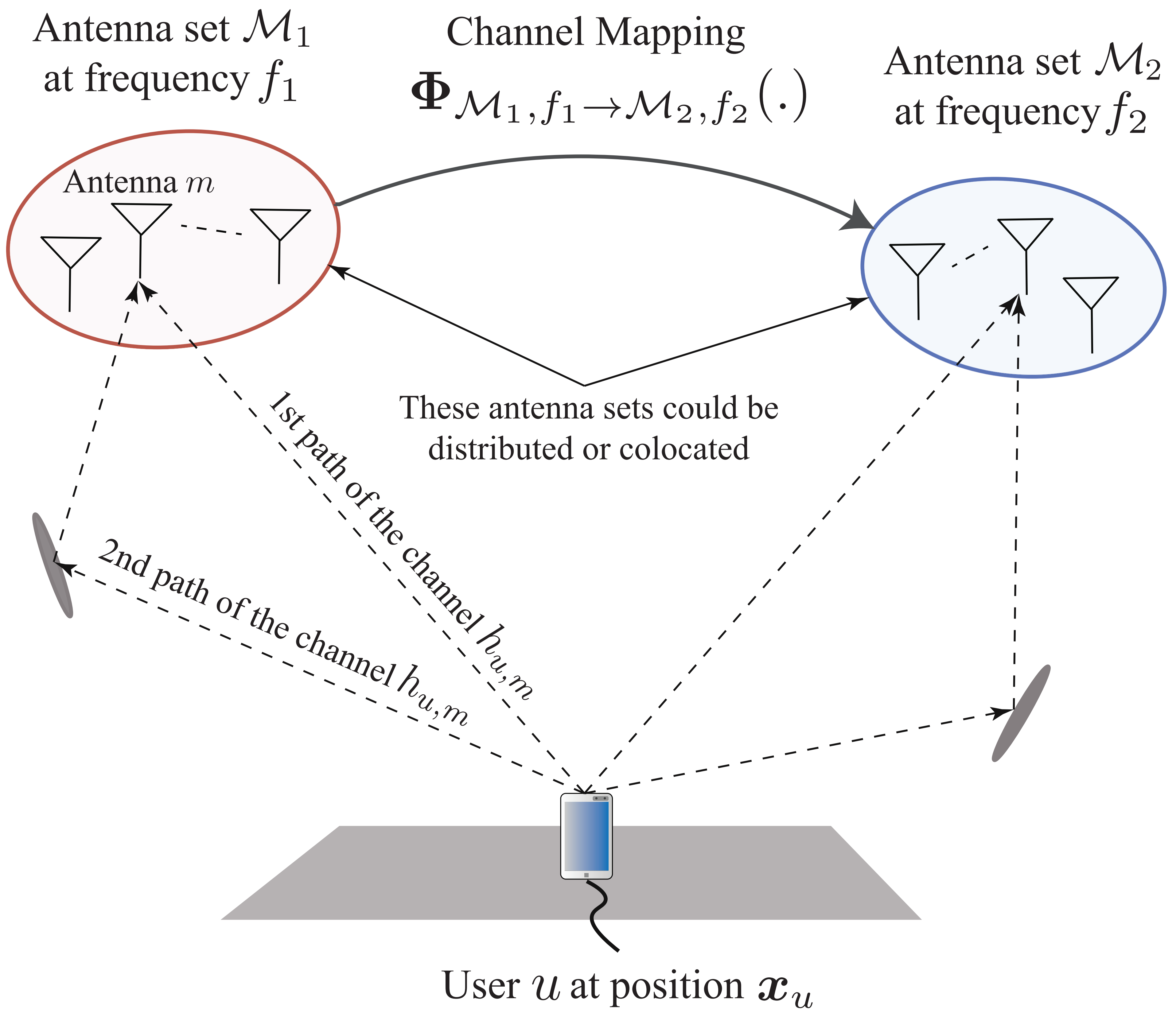
How Can Machine Learning Help?

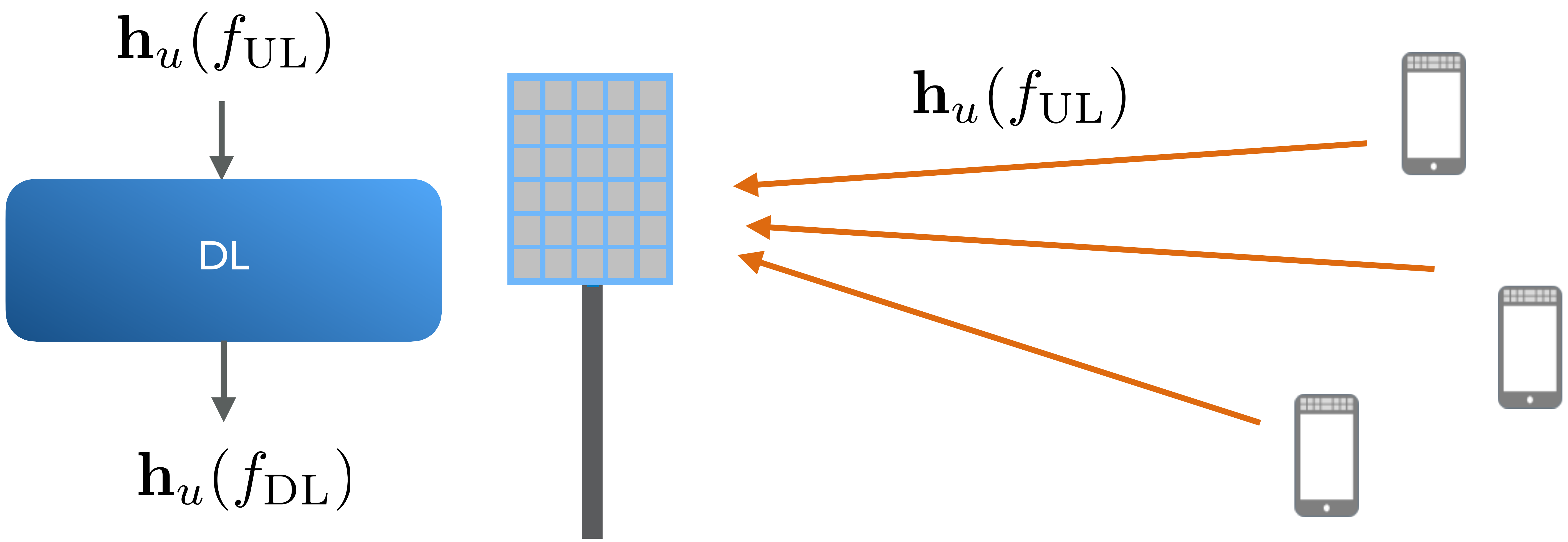


Limited observability in baseband

Higher cost and power consumption

Example: Learning complex mapping





UL/DL channel prediction

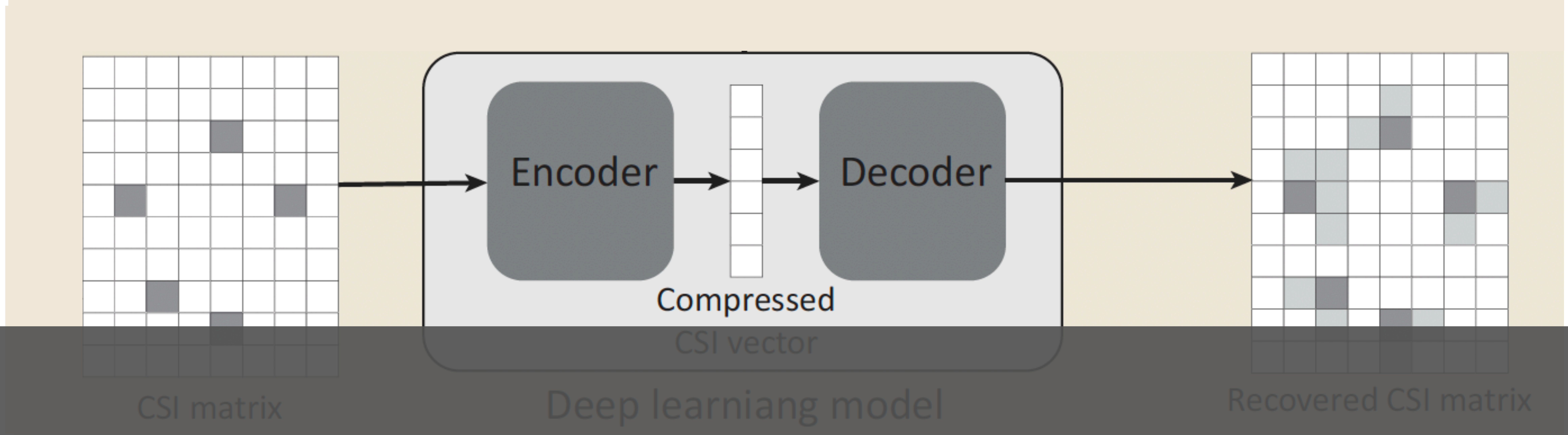
Channel tracking

Spatial/temporal beam prediction

Activity recognition

Presence detection

Example: Representation learning



Channel Compression

Beam Codebook Learning

Channel Charting

Sensing activity Clustering

But realizing these ML gains in practice has challenges

Challenges with complex communication/sensing ML tasks

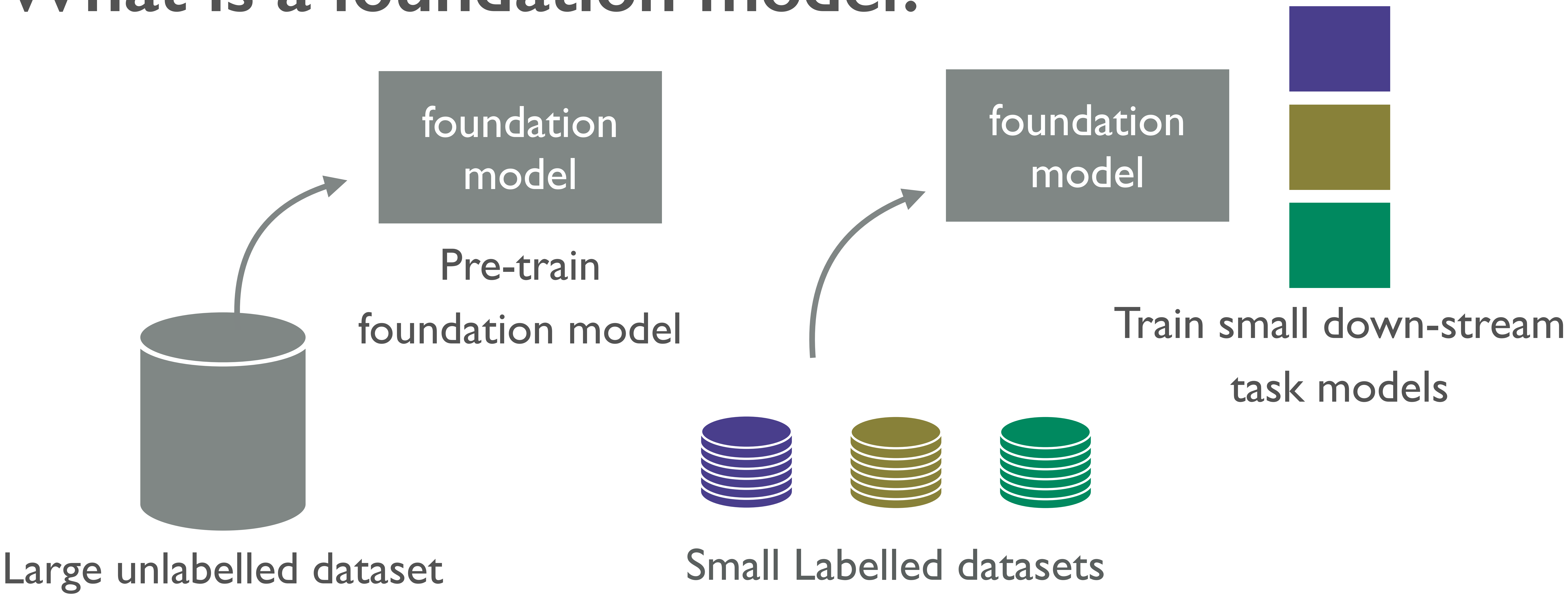
Need large labelled datasets

Complex and non-trivial model architecture design

Significant training hyper parameter optimization

Foundation Models

What is a foundation model?



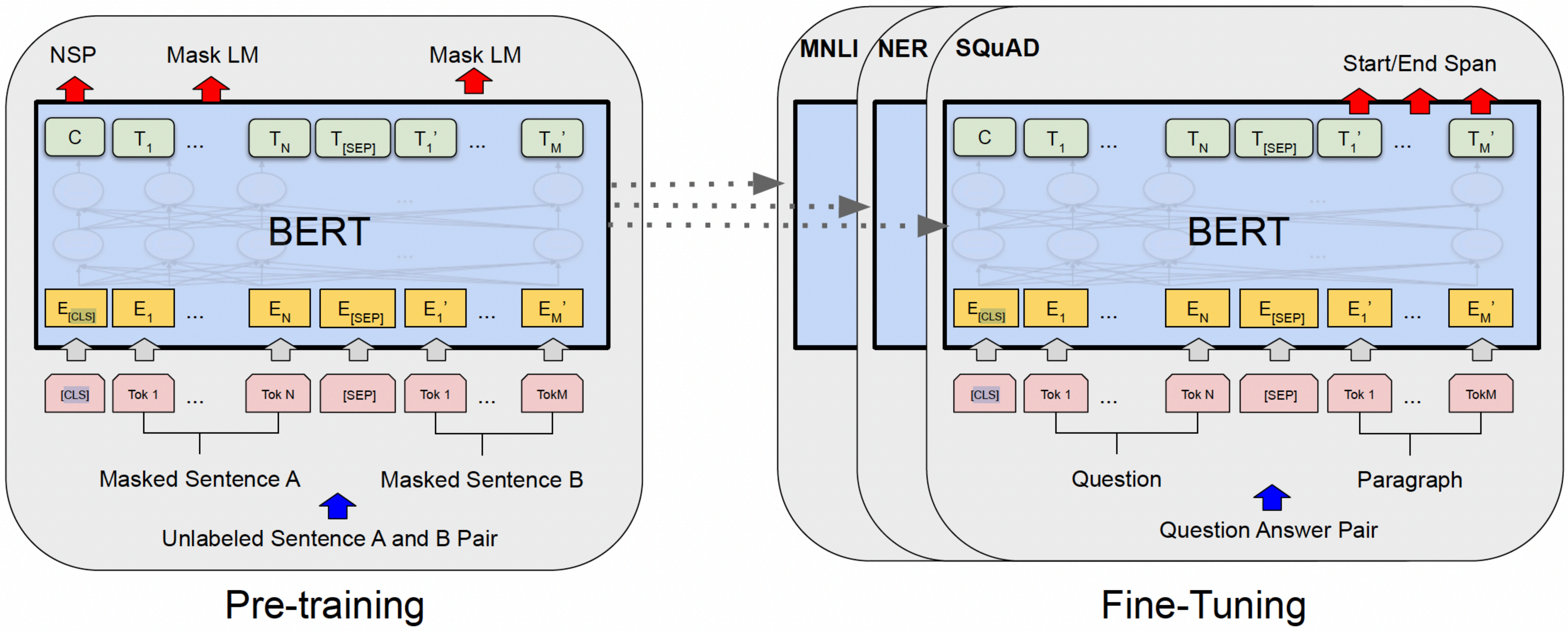
Enabling complex tasks with limited data

Simplifies model architectures for downstream tasks

Simplifies training hyper-parameter optimization

BERT in natural language processing

2018 by Google

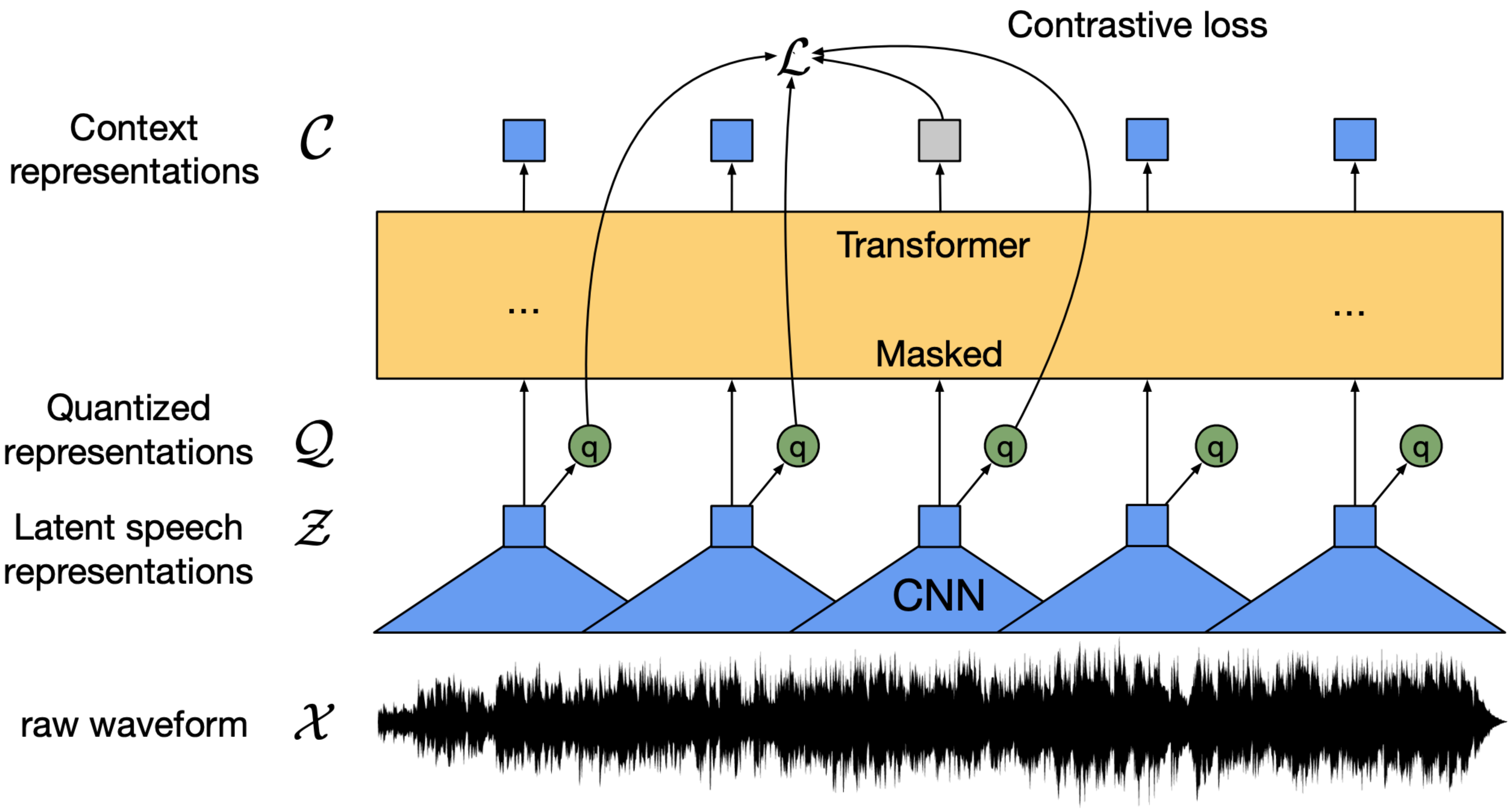


- Pre-trained on a massive dataset (including Wikipedia and BookCorpus)
- Can be fine-tuned for many tasks such as question answering and text classification

Jacob Devlin, Ming-Wei Chang, Kenton Lee, and Kristina Toutanova. 2019. BERT: Pre-training of Deep Bidirectional Transformers for Language Understanding. In *Proceedings of the 2019 Conference of the North American Chapter of the Association for Computational Linguistics: Human Language Technologies, Volume 1 (Long and Short Papers)*, pages 4171–4186

wav2vec in speech processing

2019 by Meta

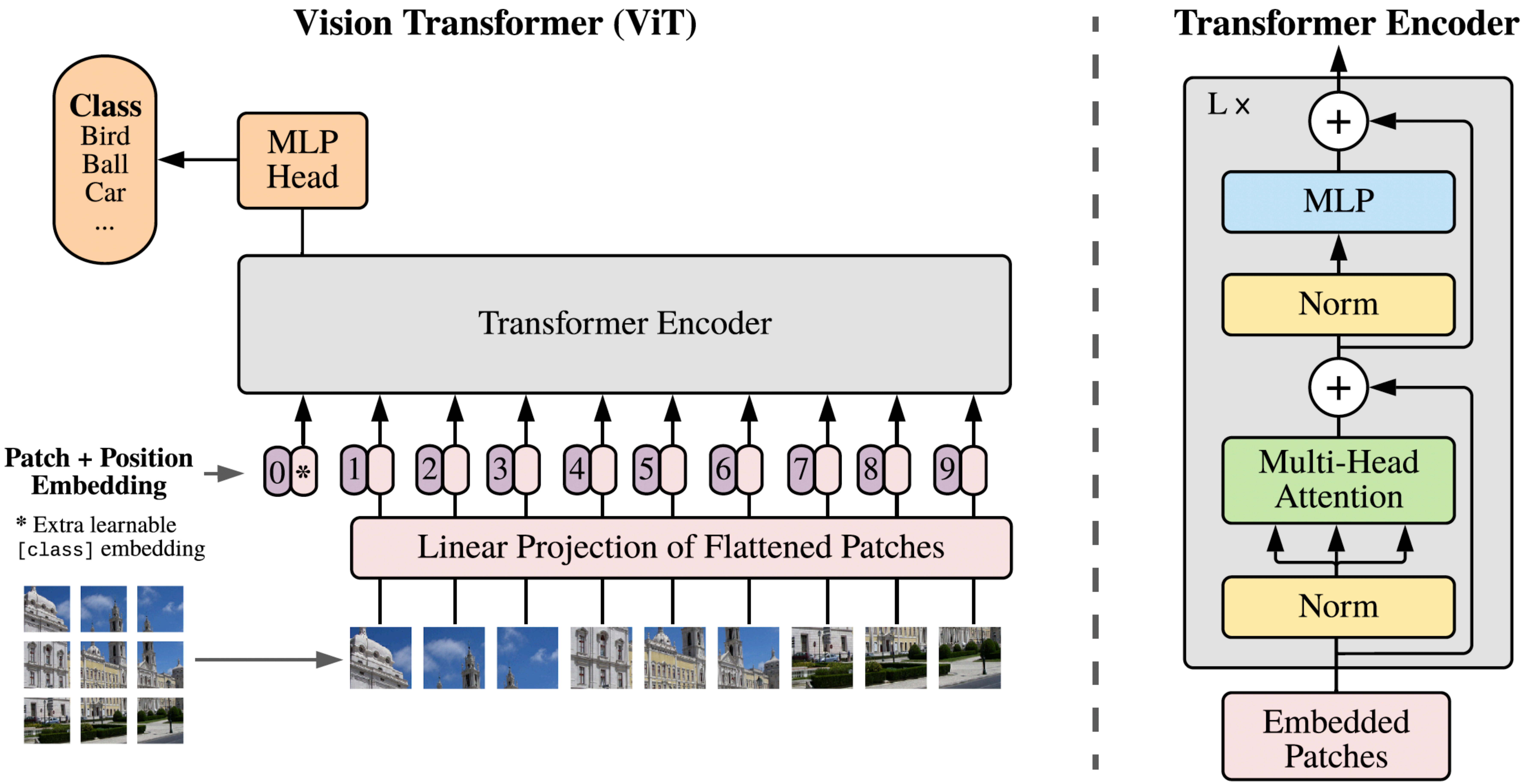


- Pre-trained on large datasets (960h LibriSpeech, 60k hours Libri-Light, 28k hours Common Voice)
- Can be fine-tuned for many tasks such as ASR and speaker identification

Schneider, S., Baevski, A., Collobert, R., & Auli, M. (2019). wav2vec: Unsupervised Pre-training for Speech Recognition. arXiv preprint arXiv:1904.05862.

ViT in computer vision

2021 by Google

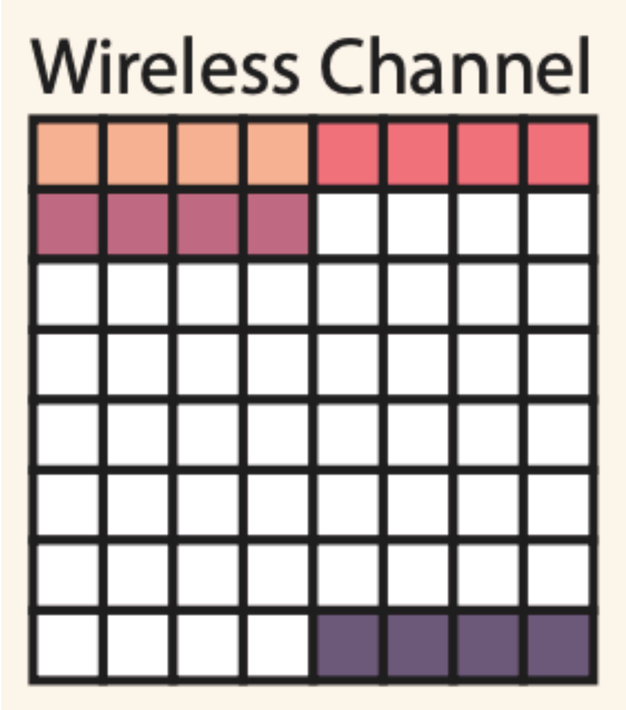


- Pre-trained on ImageNet-21k (14M images) and JFT-300M (300M images)
- Can be fine-tuned for many tasks such as image classification and object detection

Dosovitskiy, A., Beyer, L., Kolesnikov, A., Weissenborn, D., Zhai, X., Unterthiner, T., ... & Houlsby, N. (2021). *An image is worth 16x16 words: Transformers for image recognition at scale*. arXiv preprint arXiv:2010.11929.

LWMs
Large Wireless Models

LWM: World's first foundation model for wireless



LWM

Can be fine-tuned

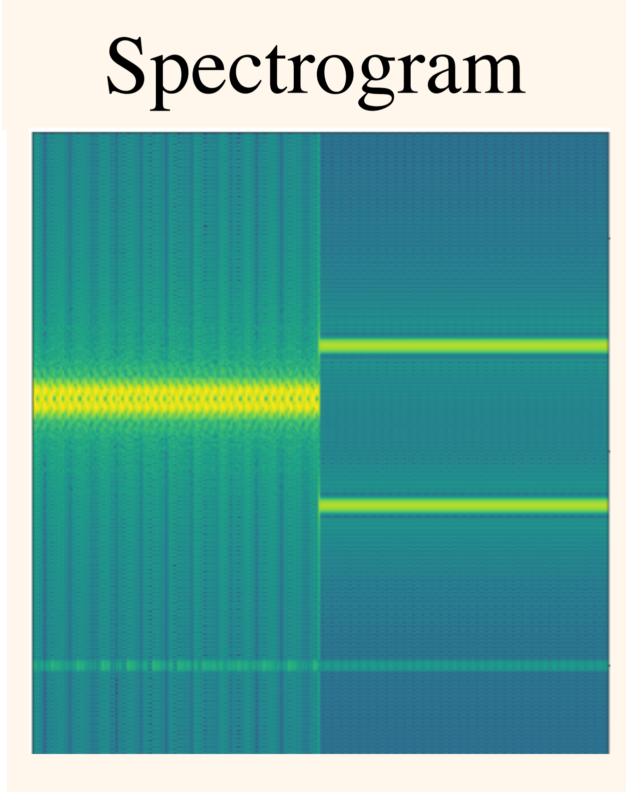
LWM 1.0 - LWM 1.1

communication tasks

LOS/NLOS classification
Beam prediction
Channel estimation
Channel interpolation
Localization

sensing tasks

Presence detection
Activity recognition
Gesture recognition
Biomarker sensing



LWM-Spectro

Can be fine-tuned

(Releasing soon!)

communication tasks

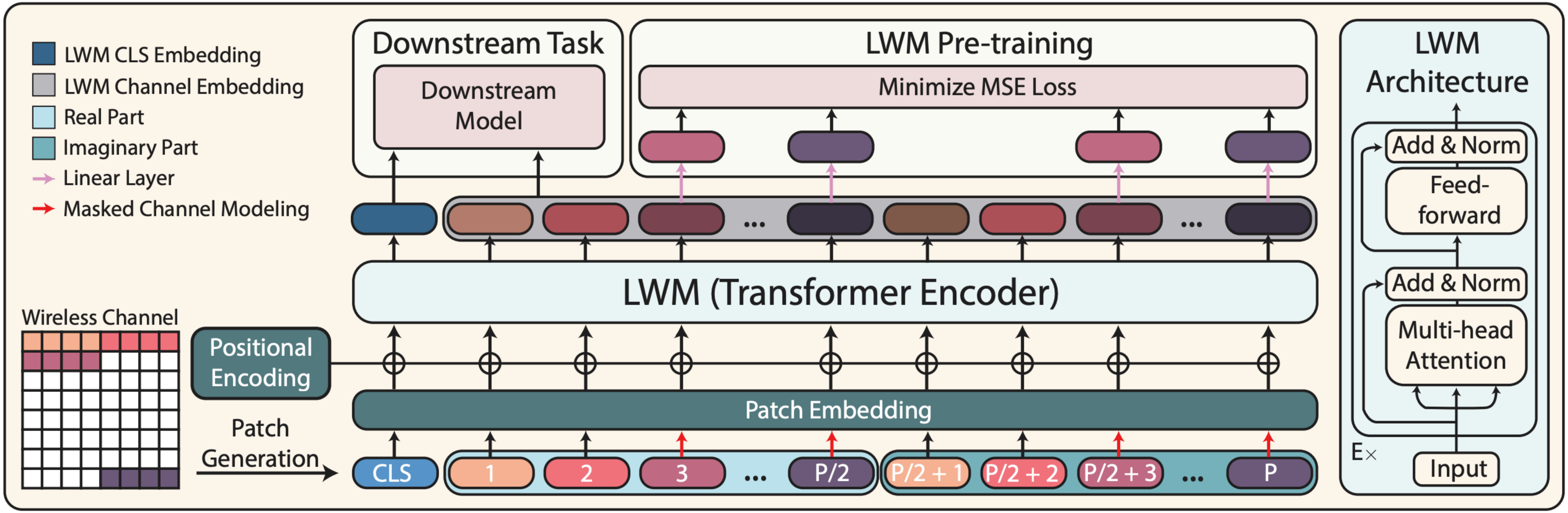
Modulation classification
Signal detection

sensing tasks

Gesture/activity recognition without cannel estimation

S. Alikhani, G. Charan, and A. Alkhateeb, **Large Wireless Model (LWM): A Foundation Model for Wireless Channels.** arXiv:2411.08872, 2024.

LWM model architecture



- The model architecture is similar to ViT while the pre-training strategy is similar to BERT
- Masked channel modeling (for real/imag. patches) is used for self-supervised pre-training
- The LWM encoder is based on the standard transformer structure

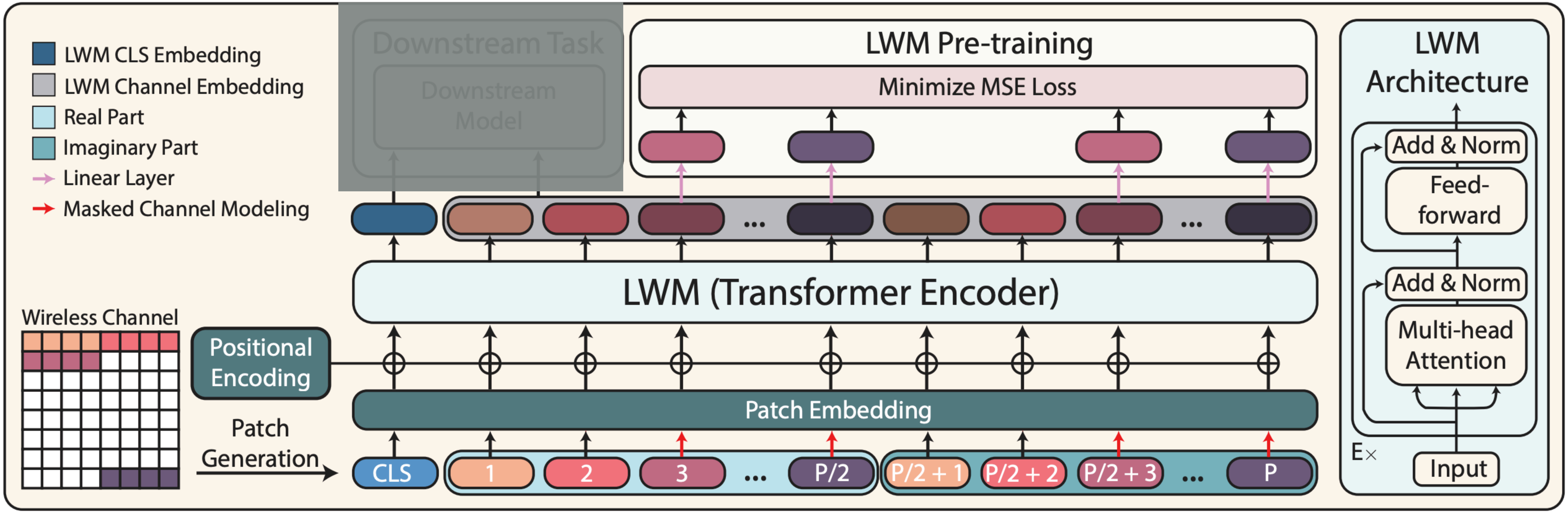
S. Alikhani, G. Charan, and A. Alkhateeb, **Large Wireless Model (LWM): A Foundation Model for Wireless Channels.** arXiv:2411.08872, 2024.

LWM pre-training — Dataset

- The DeepMIMO dataset provides diverse wireless scenarios
  - Over **1 million channel samples** are generated from **15 DeepMIMO scenarios**
  - Channels cover different number of antennas and subcarriers at basestations
  - Channels of varying sizes are used for pre-training, making the model more flexible
- Large diverse datasets help foundation models to have
  - Wide distribution coverage: Reduces domain shift across wireless environments
  - Rich embedding space: Learns generalizable, high-rank channel features
  - Improved sample efficiency: Boosts downstream performance with few labels

Find a script that generates the full data on lwm-wireless.net

LWM pre-training — Strategy

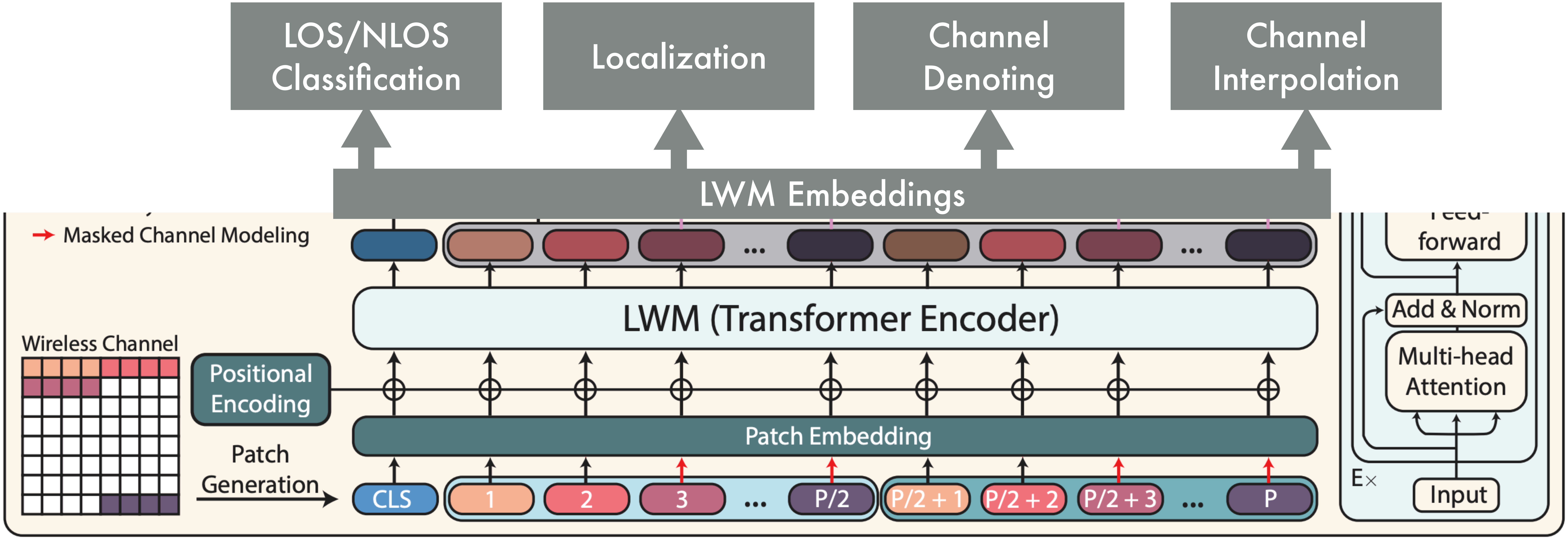


- Given the large hannel dataset, the LWM model is pre-trained end-to-end
  - Self-supervised training with masked channels via contextual channel reconstruction
  - Objective is to minimize MSE loss
- Transformer attention/multi-head mechanism implicitly learns spatial/spectral/temporal dependencies

S. Alikhani, G. Charan, and A. Alkhateeb, **Large Wireless Model (LWM): A Foundation Model for Wireless Channels.** arXiv:2411.08872, 2024.

How to use LWM?

www.LWM-wireless.net



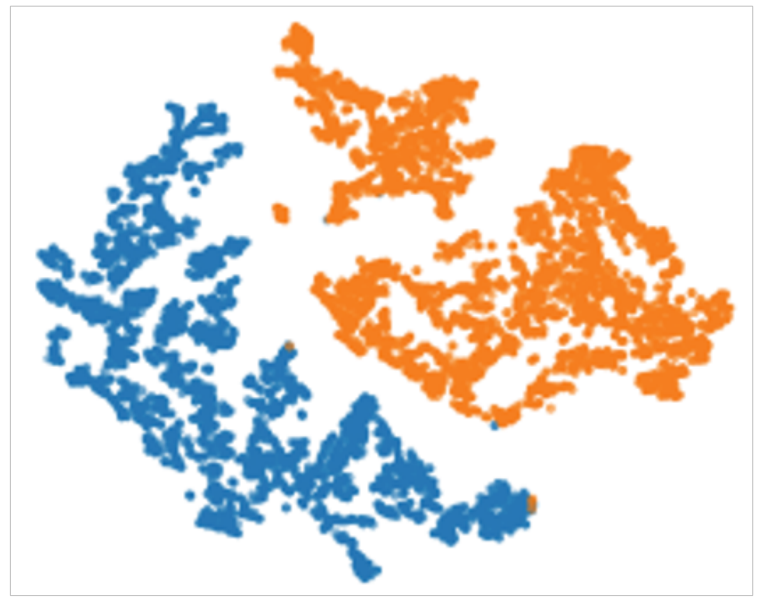
- The LWM universal embeddings could be used instead of raw-channels
- LWM embeddings can support many tasks in communications and sensing
- The model can be refined for each task (submit LWM variants for ranking & listing)

S. Alikhani, G. Charan, and A. Alkhateeb, **Large Wireless Model (LWM): A Foundation Model for Wireless Channels.** arXiv:2411.08872, 2024.

Example LWM Applications (Initial Results)

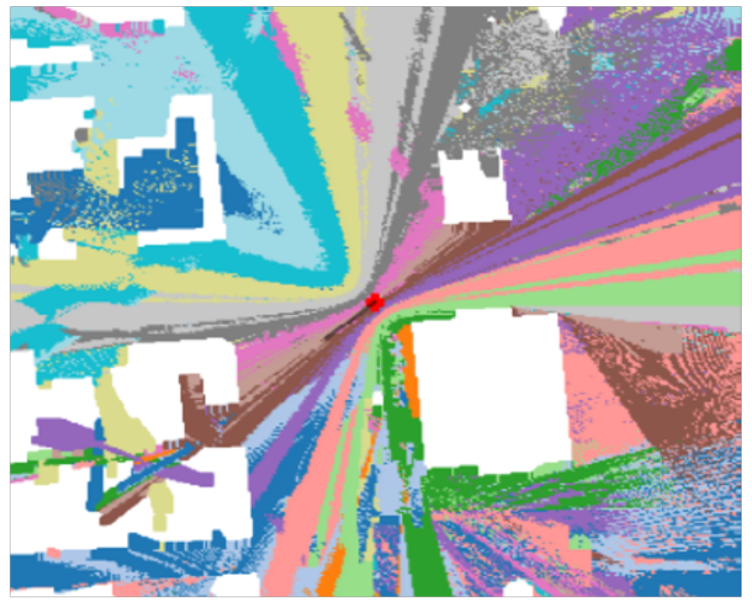
Example LWM applications

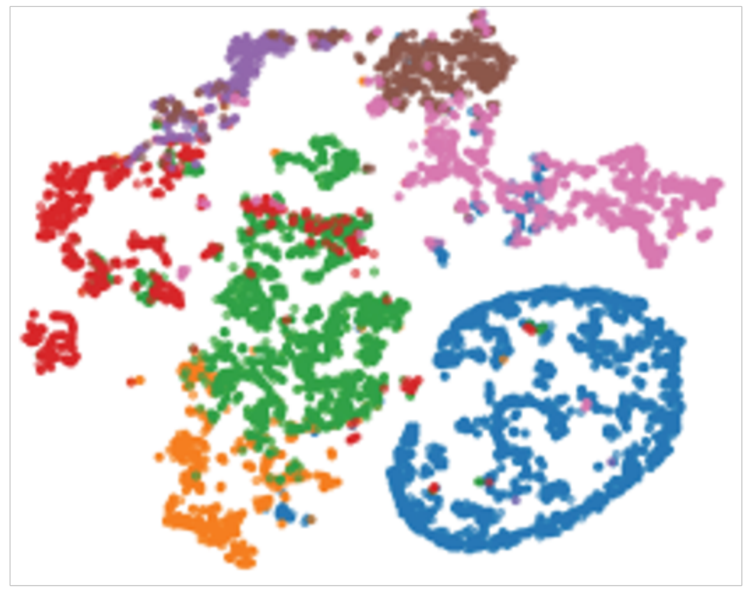
LoS/NLoS classification



Context-aware LOS/NLOS inference via global token semantics

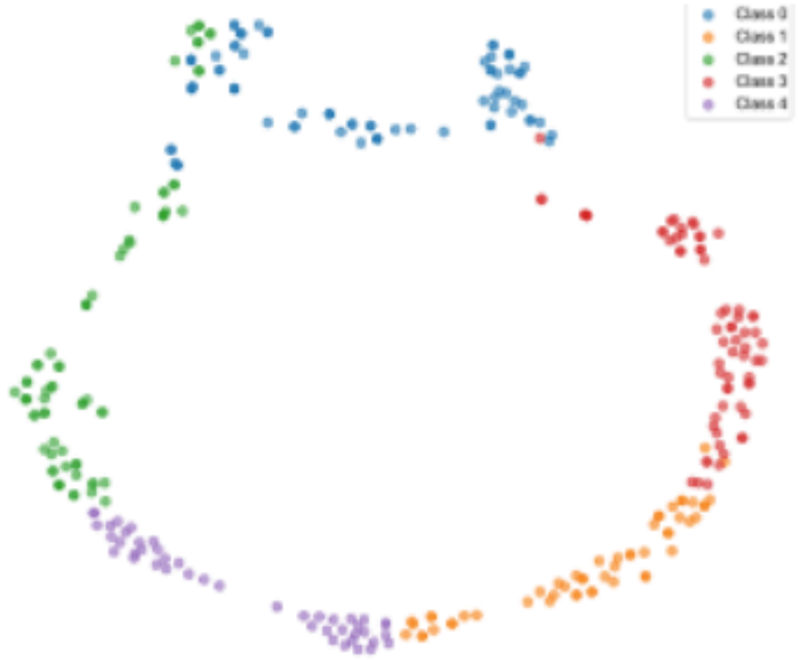
Sub6GHz channel to mmWave Beam prediction





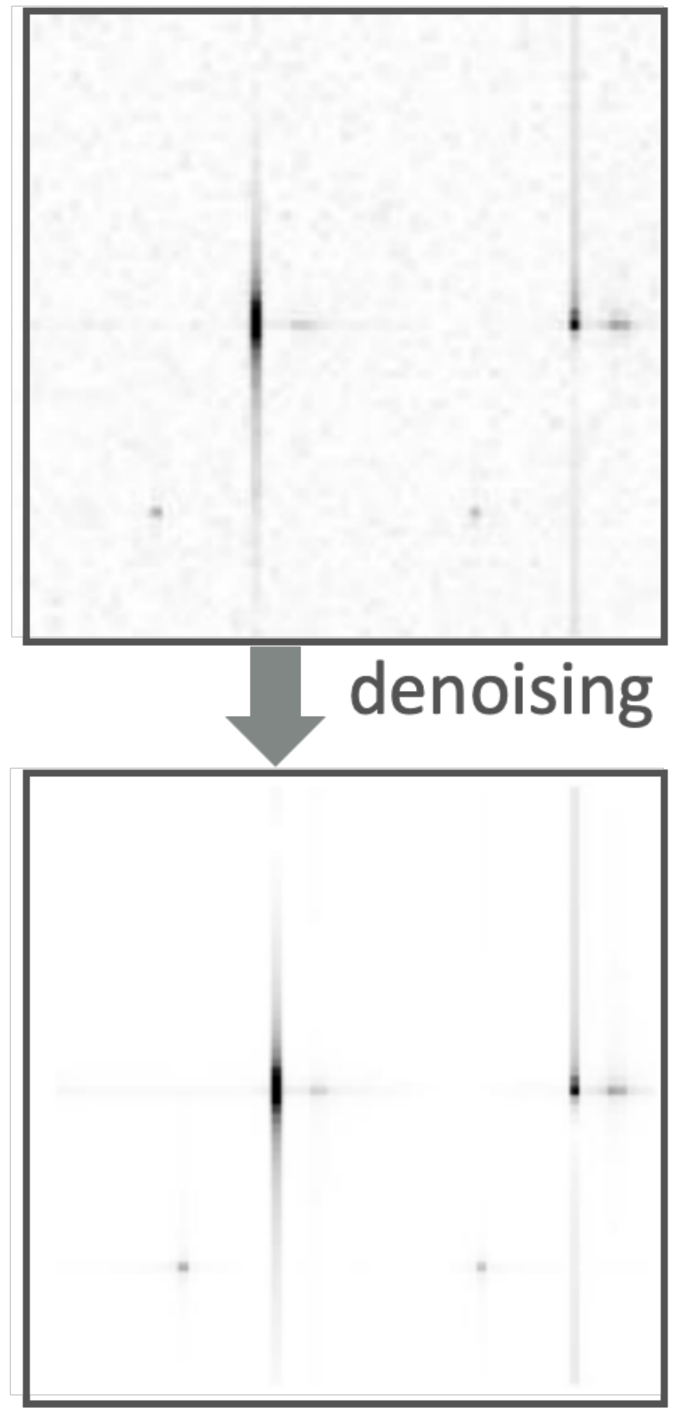
Frequency-domain knowledge transfer for mmWave beam index estimation

User localization



Geometric inference from spatially-encoded channel embeddings

Channel estimation

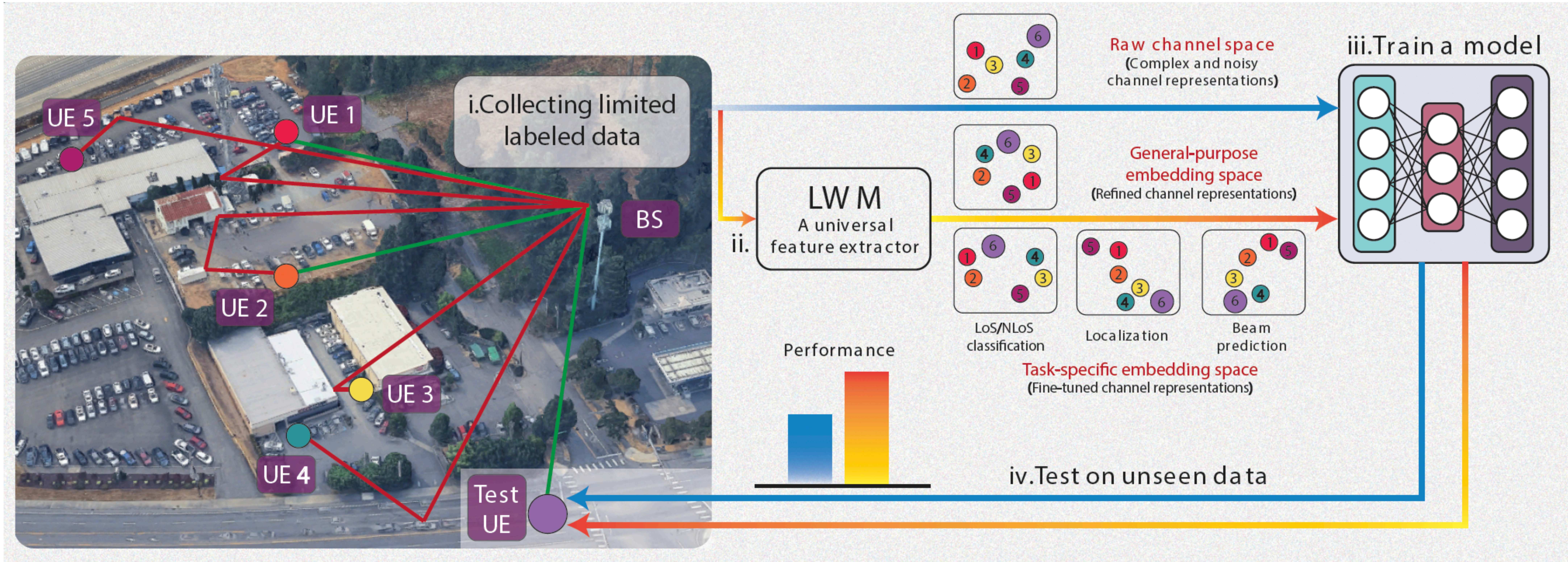


Self-supervised reconstruction of imperfect CSI via masked modeling

Channel interpolation

Self-Attention driven interpolation of missing antennas and subcarriers

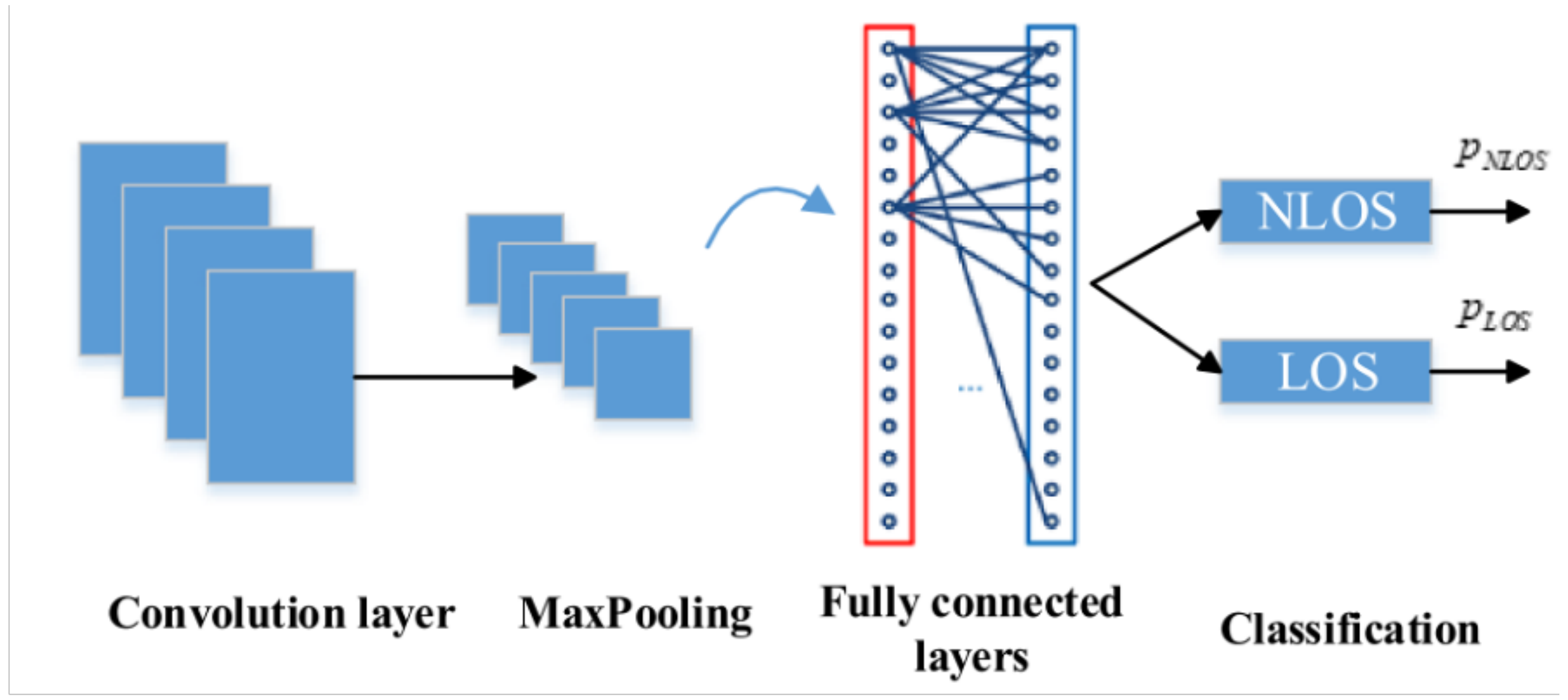
Evaluation process



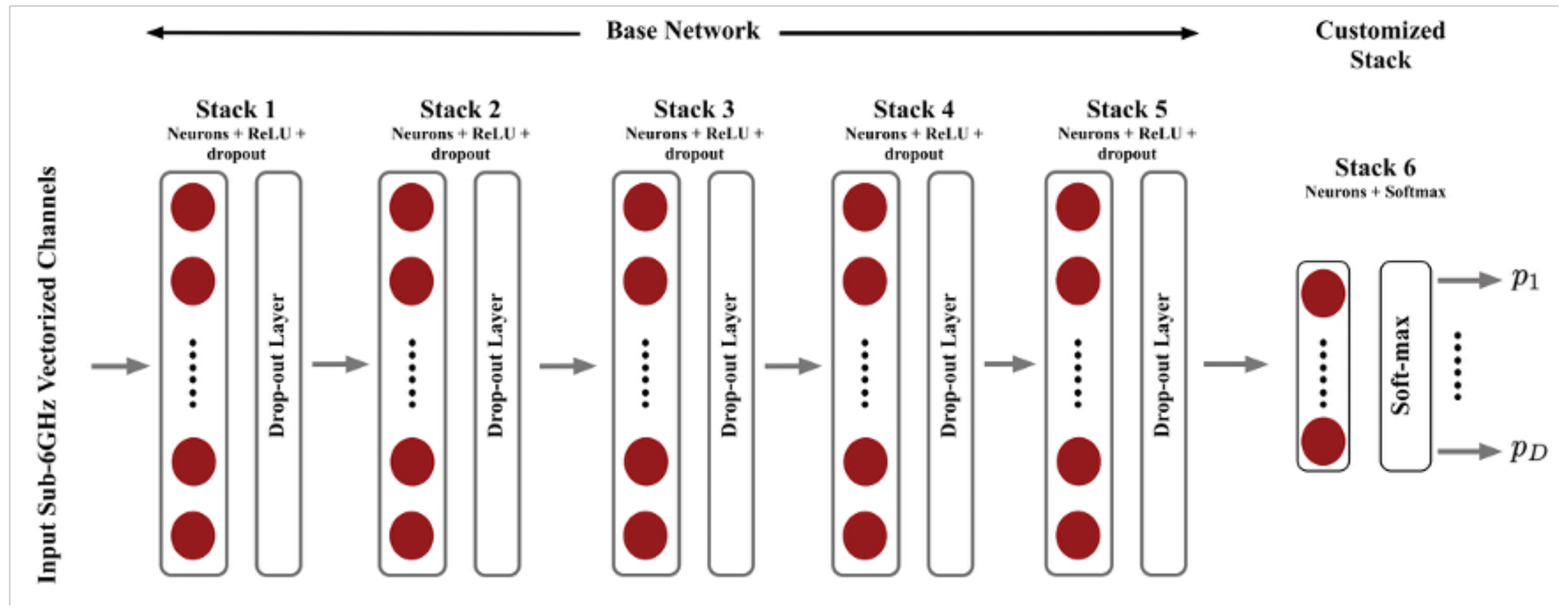
- For LWM:
  - Flattened embeddings with simple ML model generalize well
  - No specialized hyper-parameter tuning
- For the comparison
  - Adopt state of the art models (complex models and optimized training)

Considered state-of-the-art models

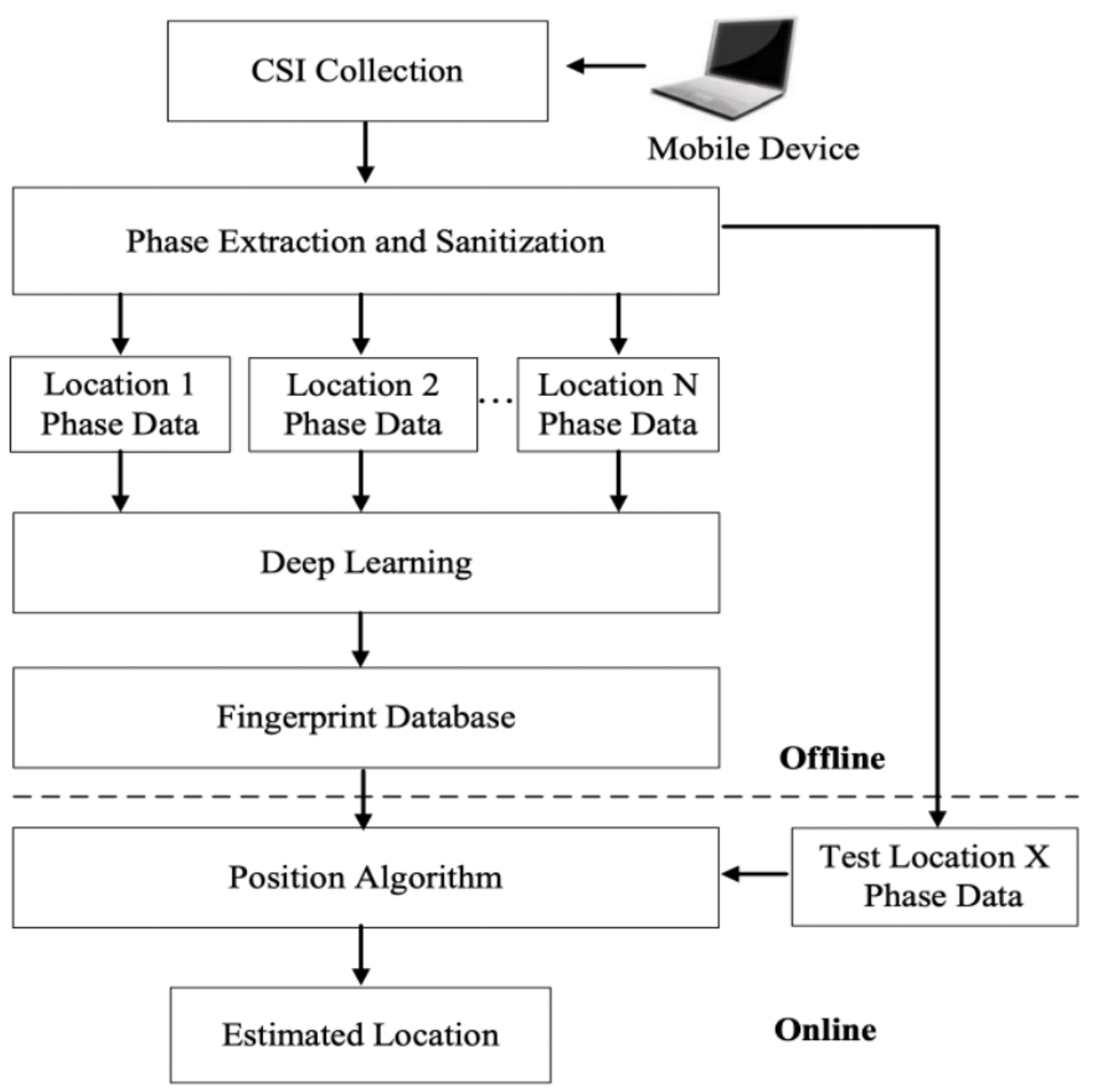
LOS/NLOS Classification
CNN



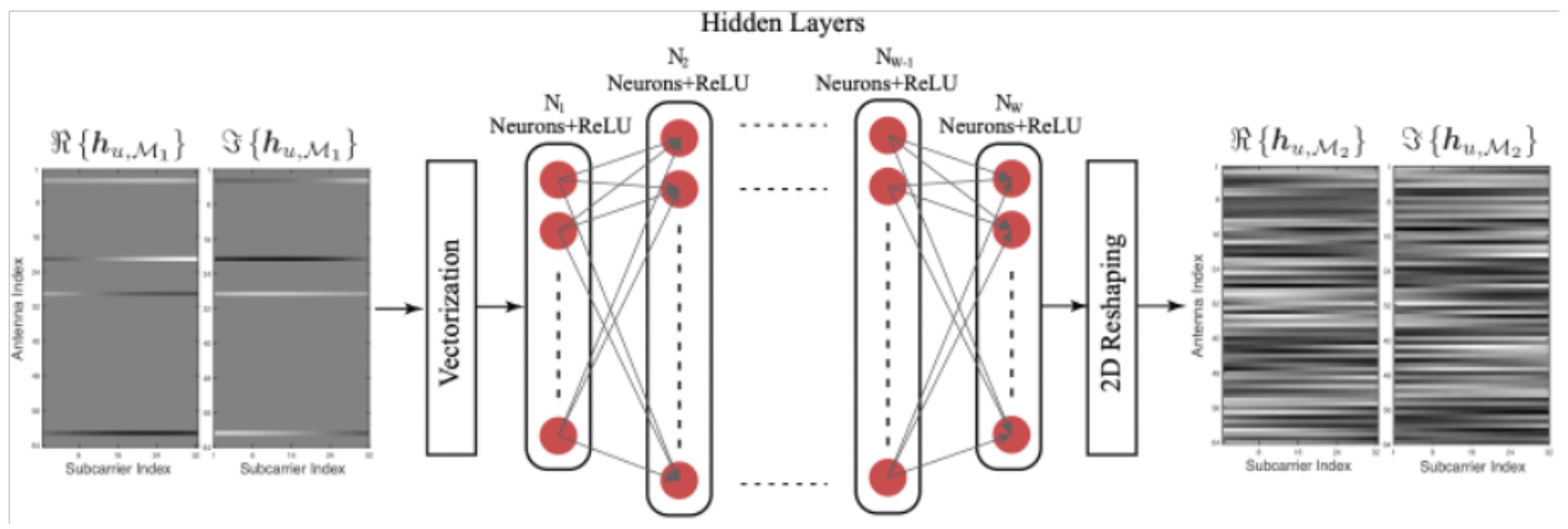
Sub-6 GHz to mmWave Beam Prediction
Complex FCN



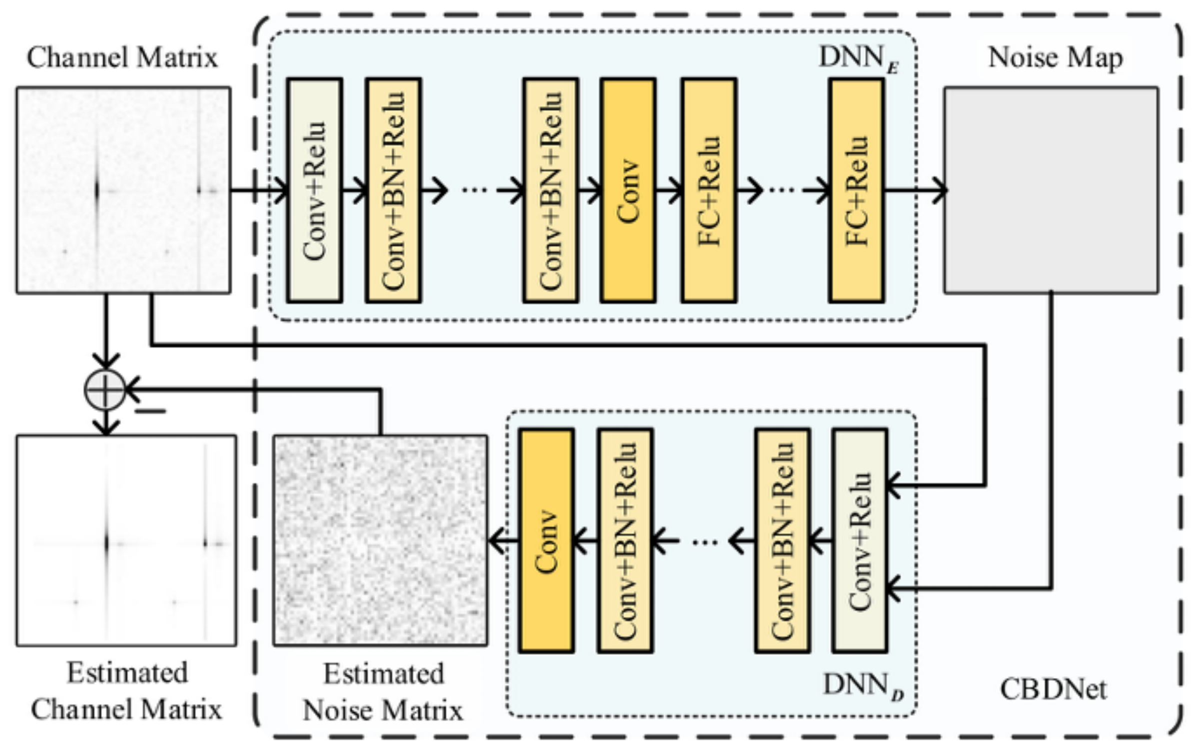
Localization
Complex FCN & data processing



Channel Interpolation
Complex FCN



Channel estimation/denoising
Complex CNN and data processing



X. Wang et al., UWB NLOS/LOS Classification, IEEE GLOBECOM, 2019.
Alrabeiah & Alkhateeb, Deep Learning for TDD/FDD Channel Mapping, Asilomar, 2019.
X. Wang, L. Gao, S. Mao and S. Pandey, "CSI-Based Fingerprinting for Indoor Localization: A Deep Learning Approach," in *IEEE Transactions on Vehicular Technology, 2017.*
J. Guo et al., Convolutional Neural Network based Multiple-Rate Compressive Sensing for Massive MIMO CSI Feedback: Design, Simulation, and Analysis, arXiv:1906.06007, 2019.

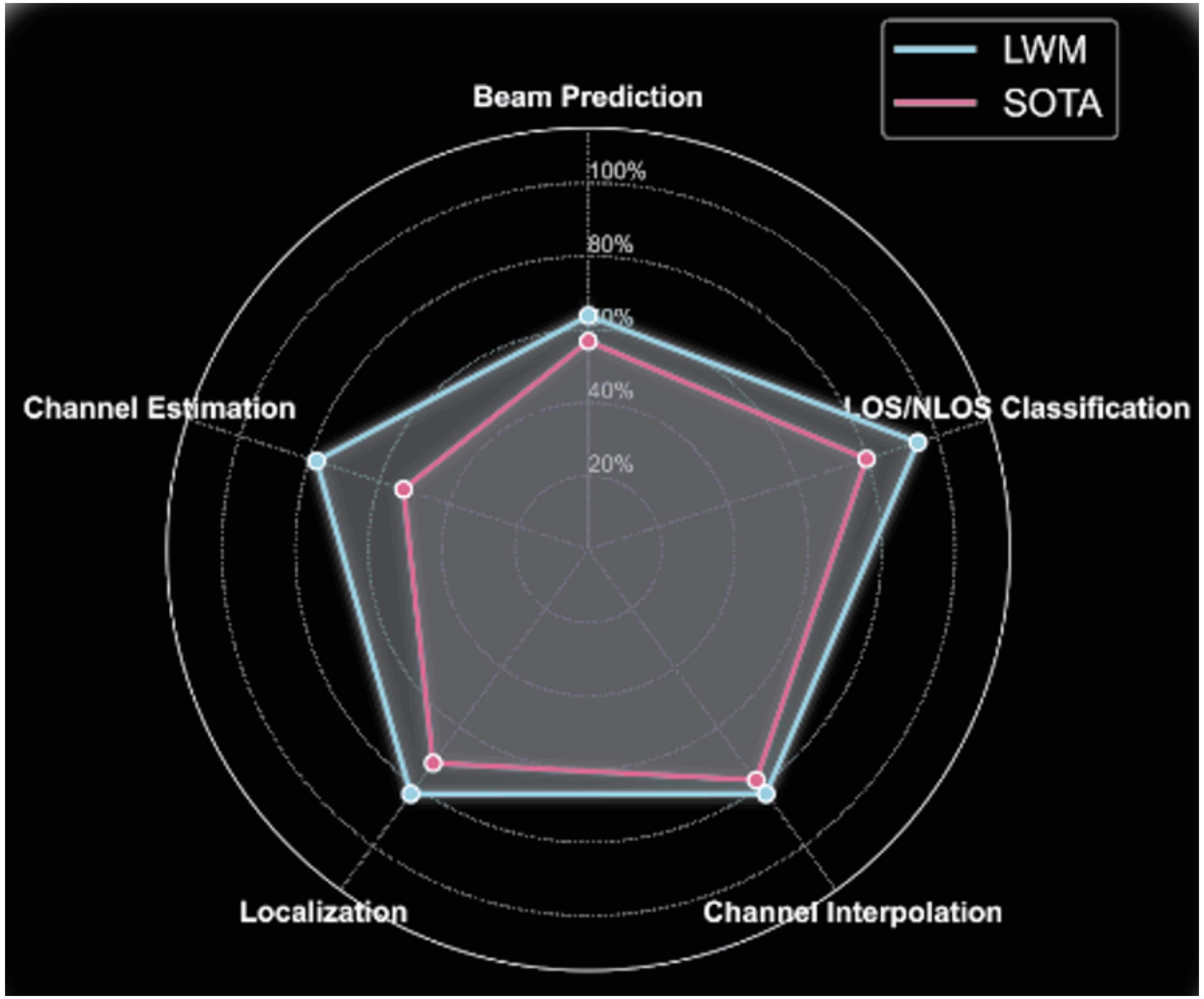
Typically relies on complex task and data specific designs with increased risk of overfitting with limited data

Initial LWM results

LWMs lead to

- Better gains
- Simple downstream model design
- Simple training

Huge room for optimization!



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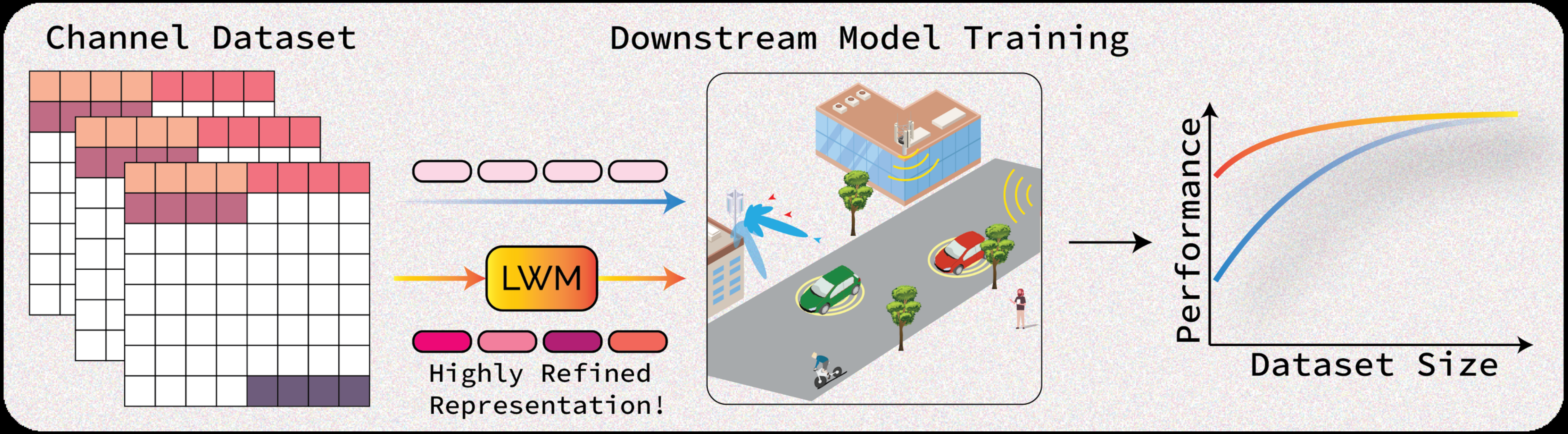
LWM ITU ML Competition

ITU ML Challenge 2025

LWM Multi-Task Optimization

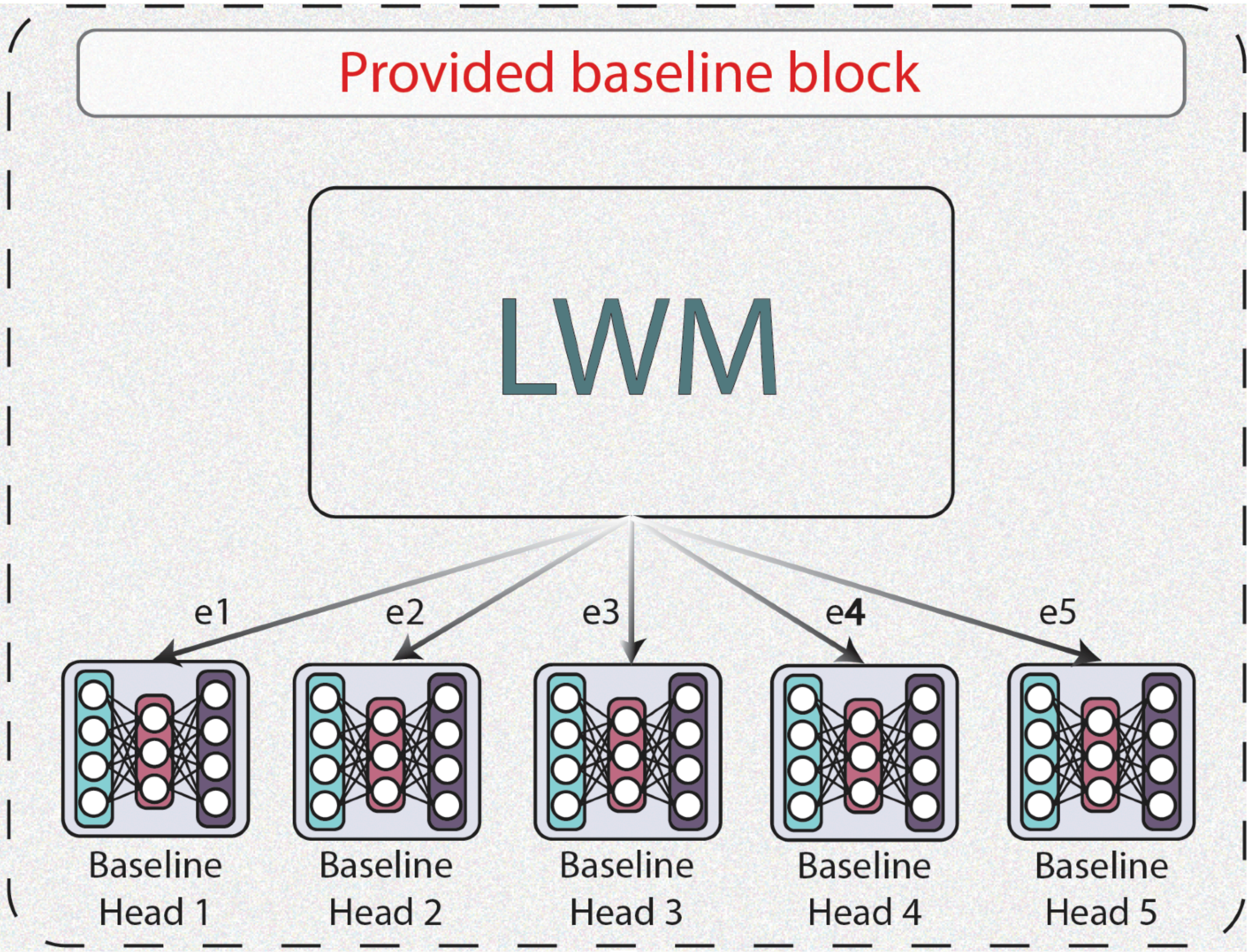


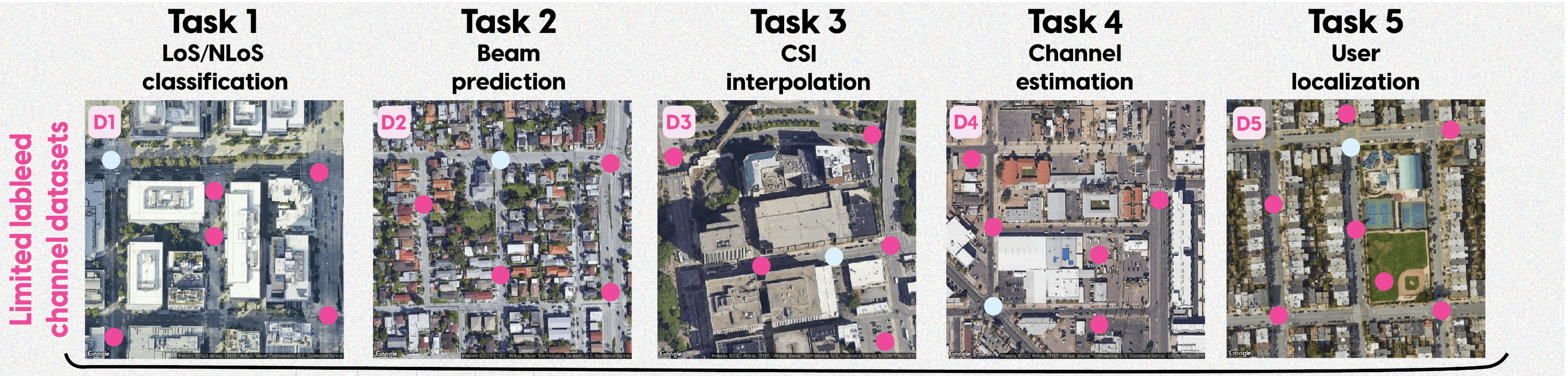
Wireless Intelligence Lab

AI for Good

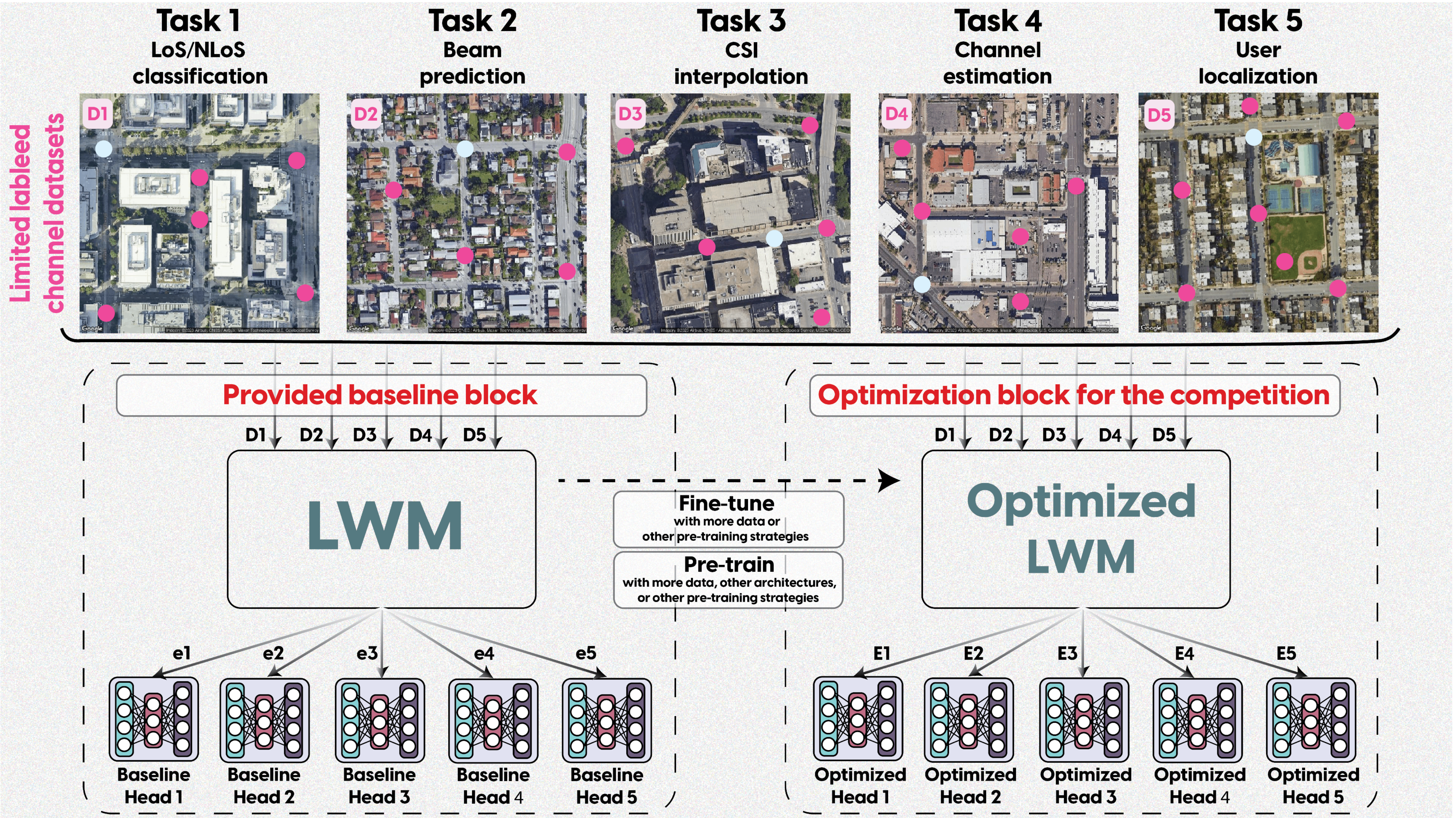
Problem Statement

- Participants will be provided with
  - A baseline pre-trained LWM 1.1 model
  - Baseline models for five downstream tasks
  - Limited training/test sets for the five tasks

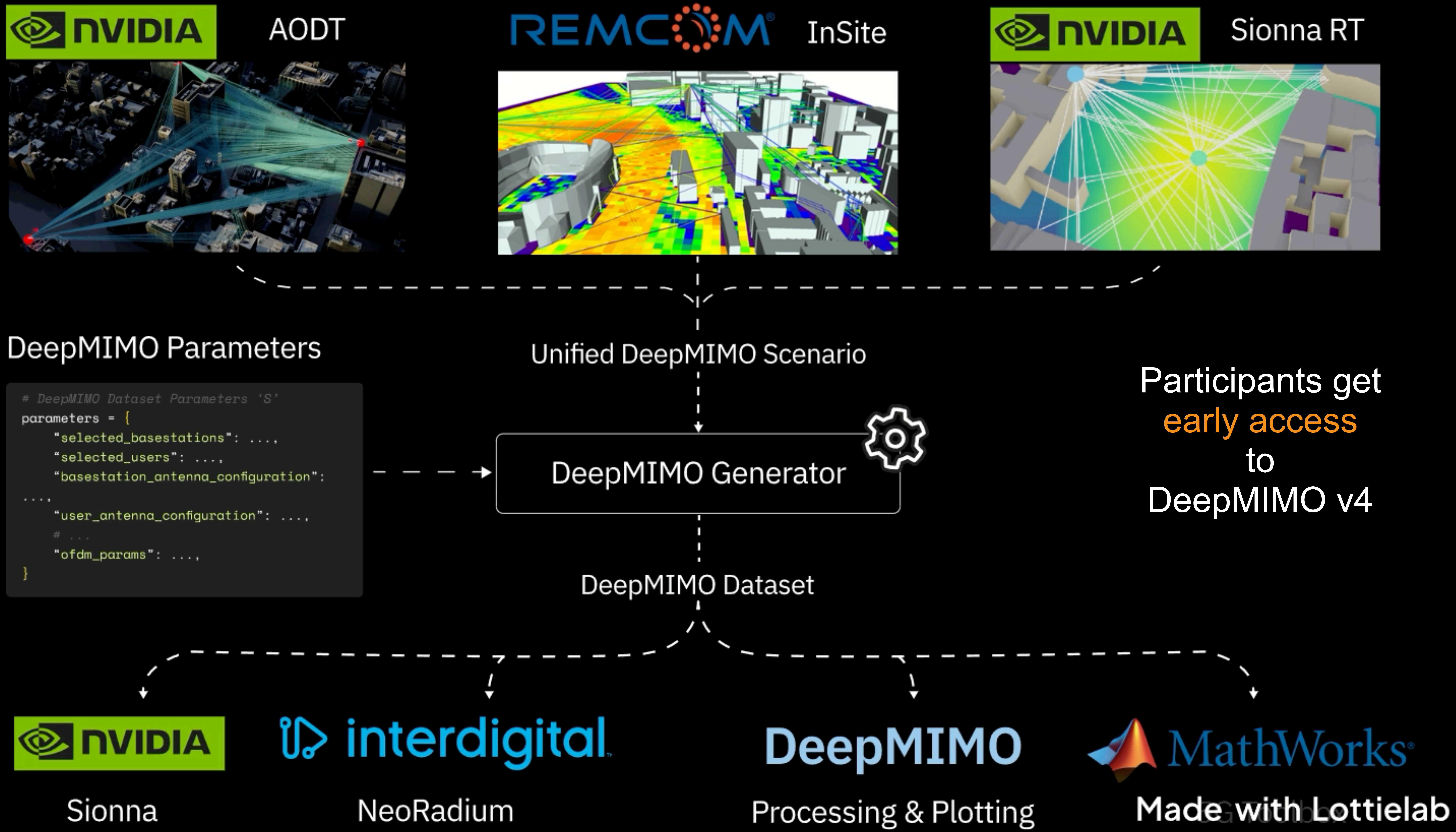




Problem Statement



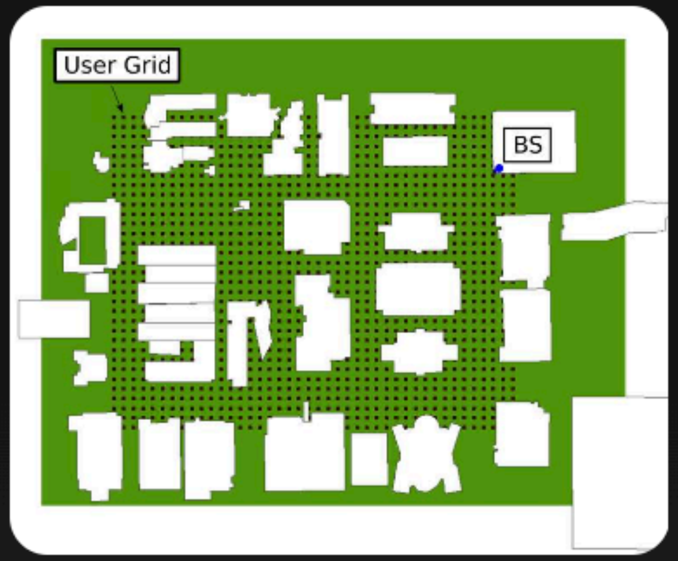
Participants can refine the LWM or downstream task models/training


NVIDIA
AODT
REMCOM
InSite
NVIDIA
Sionna RT
DeepMIMO Parameters
# DeepMIMO Dataset Parameters 'S'
parameters = {
"selected_basestations": ....,
"selected_users": ....,
"basestation_antenna_configuration": ....,
"user_antenna_configuration": ....,
...
"ofdm_params": ....,
}
Unified DeepMIMO Scenario
DeepMIMO Generator
DeepMIMO Dataset
Participants get
early access
to
DeepMIMO v4
NVIDIA
Sionna
interdigital
NeoRadium
DeepMIMO
Processing & Plotting
MathWorks
Made with Lottielab

DeepMIMO v4
with 200+ datasets

Version 4 Scenarios

Facilitating
community contributions



asu_campus_3p5

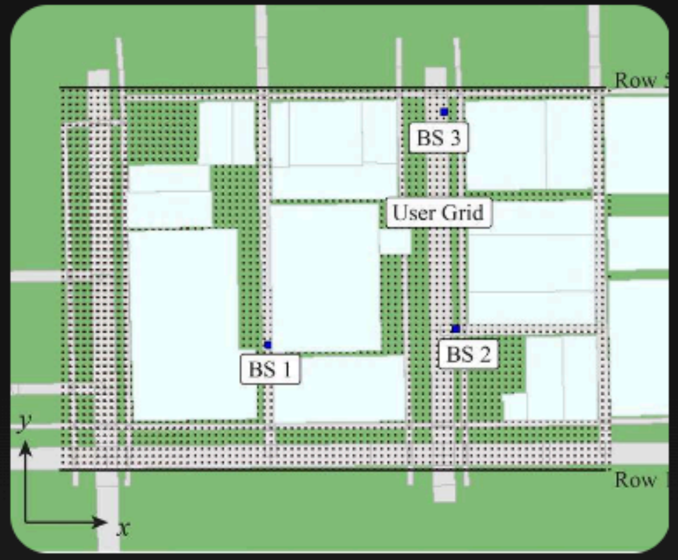
A scenario for asu_campus_3p5

city_0_newyork_3p5

A scenario for city_0_newyork_3p5

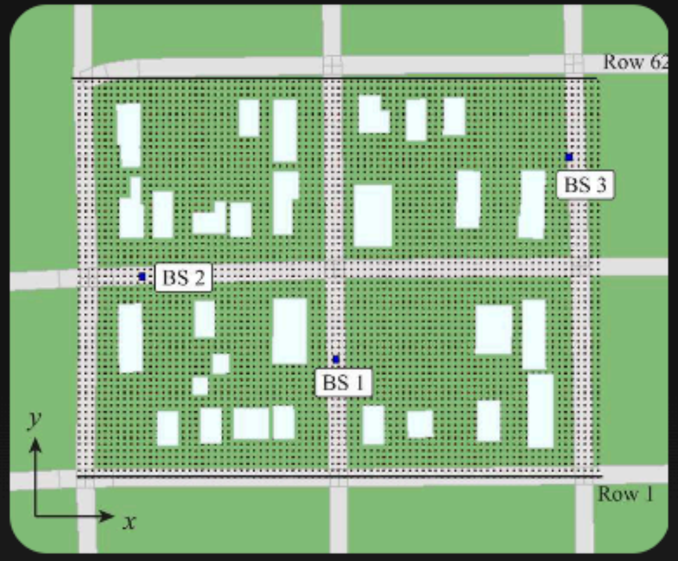
city_1_losangeles_3p5

A scenario for city_1_losangeles_3p5



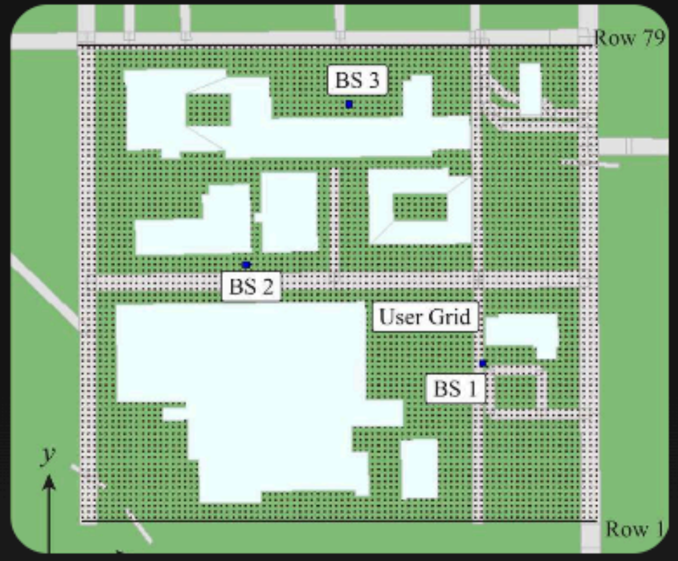
city_2_chicago_3p5

A scenario for city_2_chicago_3p5



city_3_houston_3p5

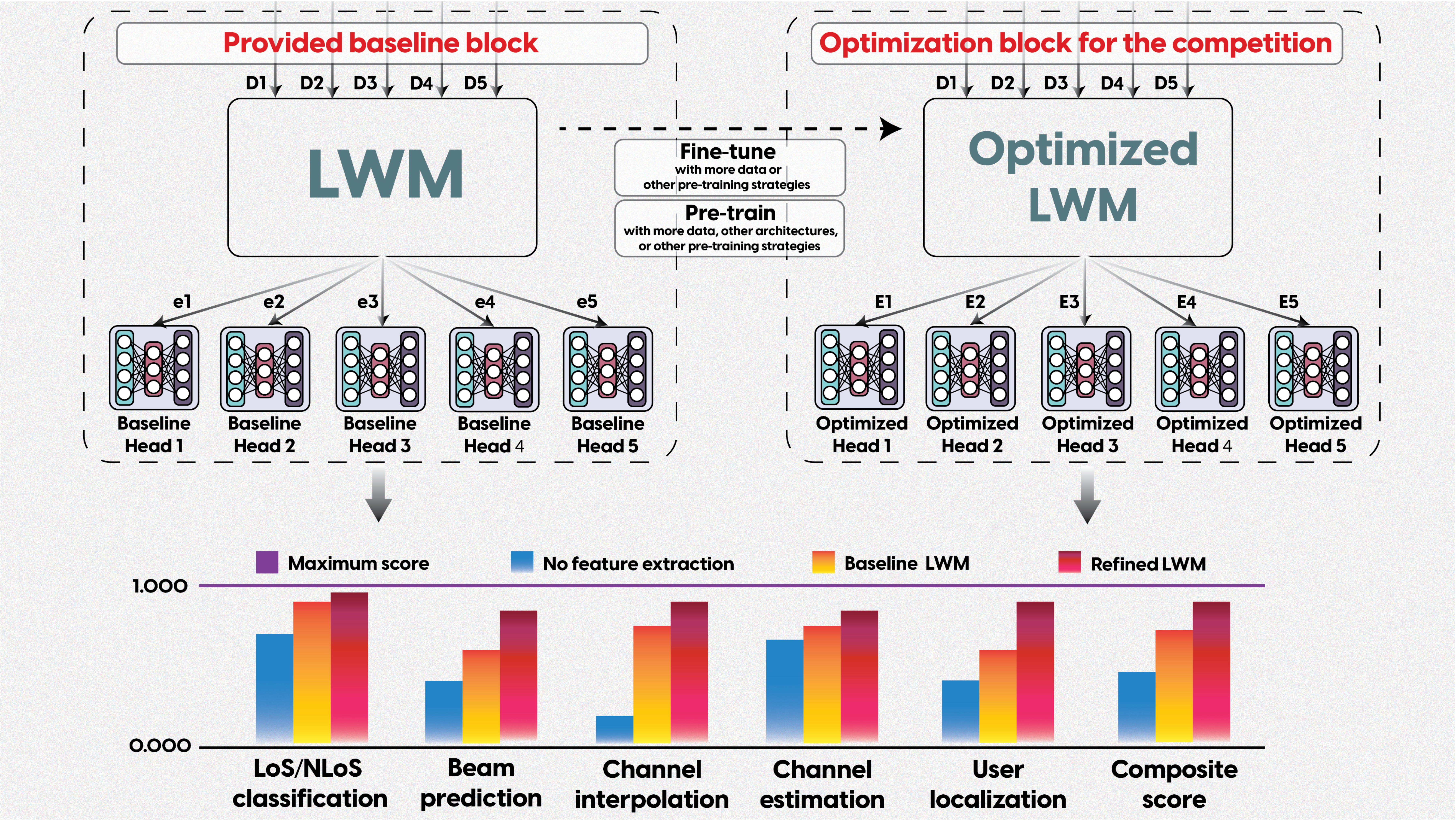
A scenario for city_3_houston_3p5



city_4_phoenix_3p5

A scenario for city_4_phoenix_3p5

Problem Statement



Registration is now open!

Final models will be ranked on the LWM website!

Participants will submit refined models and prediction results

Evaluation will be based on the composite score of the five tasks

Conclusion

- Complex communication/sensing ML tasks are challenging
  - Require large datasets (site-specific)
  - Non-trivial model architectures and training optimization

- LWMs: World's first foundation model for wireless
  - Enable complex tasks with small datasets and simple downstream models
  - Support many communication and sensing tasks
  - Stay tuned for more LWM releases coming soon!

Registration is now open for the
ITU ML Challenge 2025 on LWMs

www.LWM-wireless.net | www.WI-Lab.net | www.DeepMIMO.net

Thank You!

Questions?

www.DeepSense6G.net | www.WI-Lab.net | www.DeepVerse6G.net