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NATIONAL YANG MING CHIAO TUNG UNIVERSITY

Lecture 5 : Radio Maps for 6G

Class GitHub: https://github.com/NYCU-ICCLab/sionna_introduction
NVIDIA website: https://developer.nvidia.com/sionna
Sionna official tutorial: https://nvlabs.github.io/sionna/index.html
Sionna GitHub: https://github.com/NVlabs/sionna

Physical-Layer tooling, isn't Matlab enough?

- **Need for 6G-ready tools**: As the industry moves towards 6G, researchers require simulation frameworks capable of handling unprecedented modeling accuracy and scale.

- **Integration of AI/ML**: There's a growing need for link-level simulators with native machine learning integration and automatic gradient computation.

- **Environment-specific simulations**: Many 6G technologies demand simulations of specific environments with spatially consistent correspondence between physical location, wireless channel impulse response, and visual input.

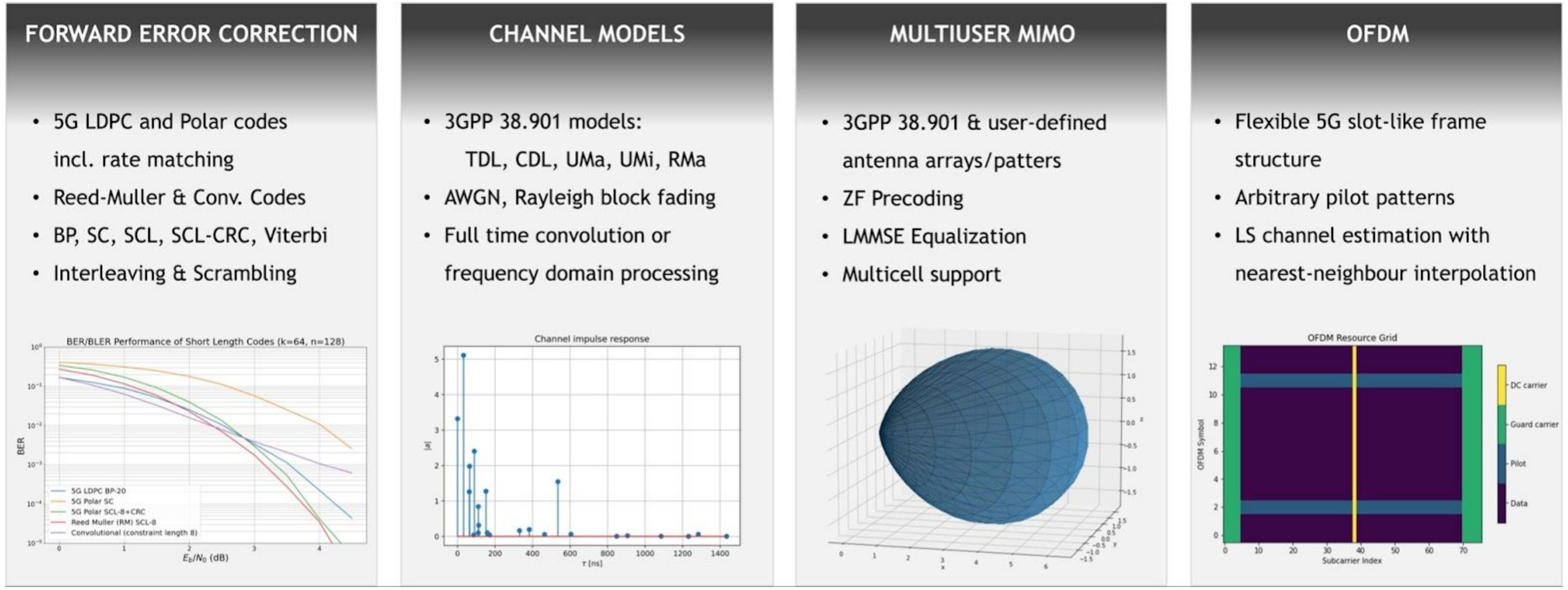
- **Computational efficiency**: The complexity of modern wireless systems necessitates GPU-accelerated simulations to enable interactive exploration and rapid prototyping

courtesy : NVIDIA Sionna

Importance of PHY Layer simulation

- **Open-source and accessible**: As researcher and student, the needs for an accessible tools becomes important → As an open-source library, Sionna democratizes 6G research, allowing researchers to focus on impactful and reproducible work.

- **Differentiability**: Sionna's differentiable architecture enables gradient-based optimization and seamless integration of neural networks into communication systems.



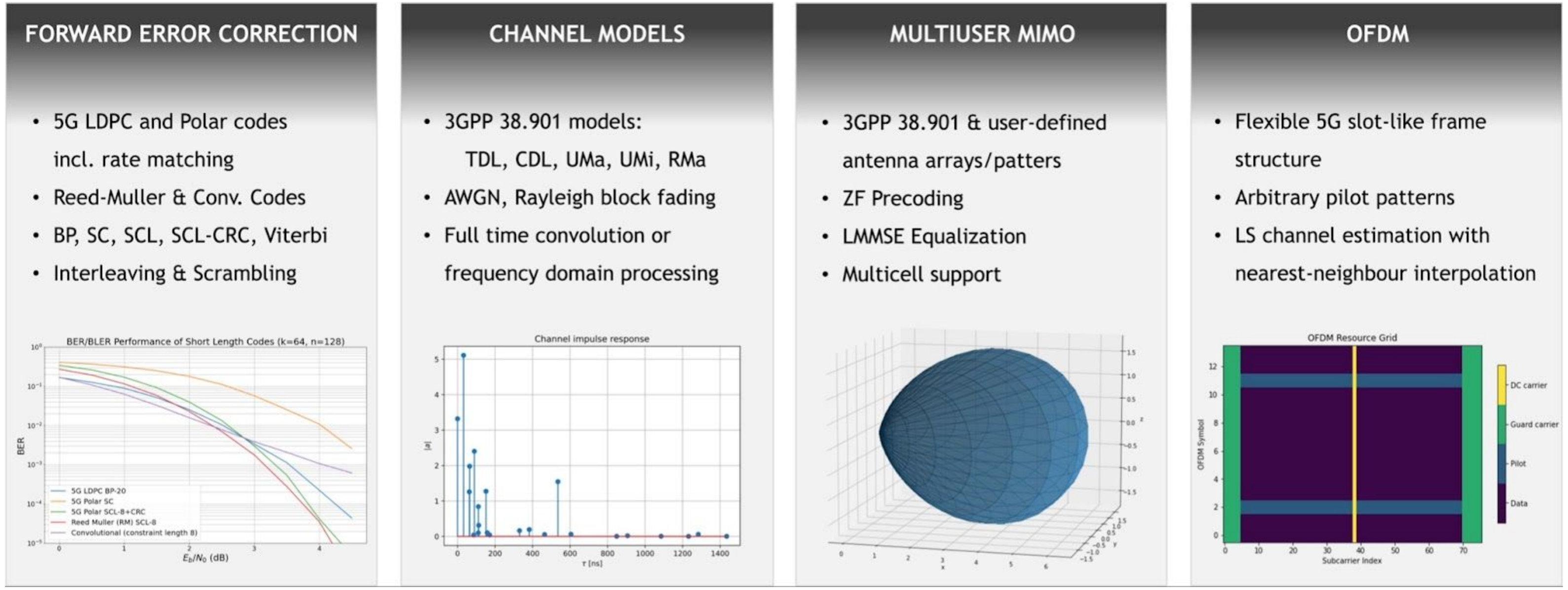
courtesy : Sionna Documentation

Importance of PHY Layer simulation

- **Modular design**: The framework's modular and extensible nature facilitates rapid prototyping of complex communication system architectures.

- **GPU acceleration**: Sionna leverages NVIDIA GPUs for orders-of-magnitude faster simulations, enabling interactive exploration of complex systems.

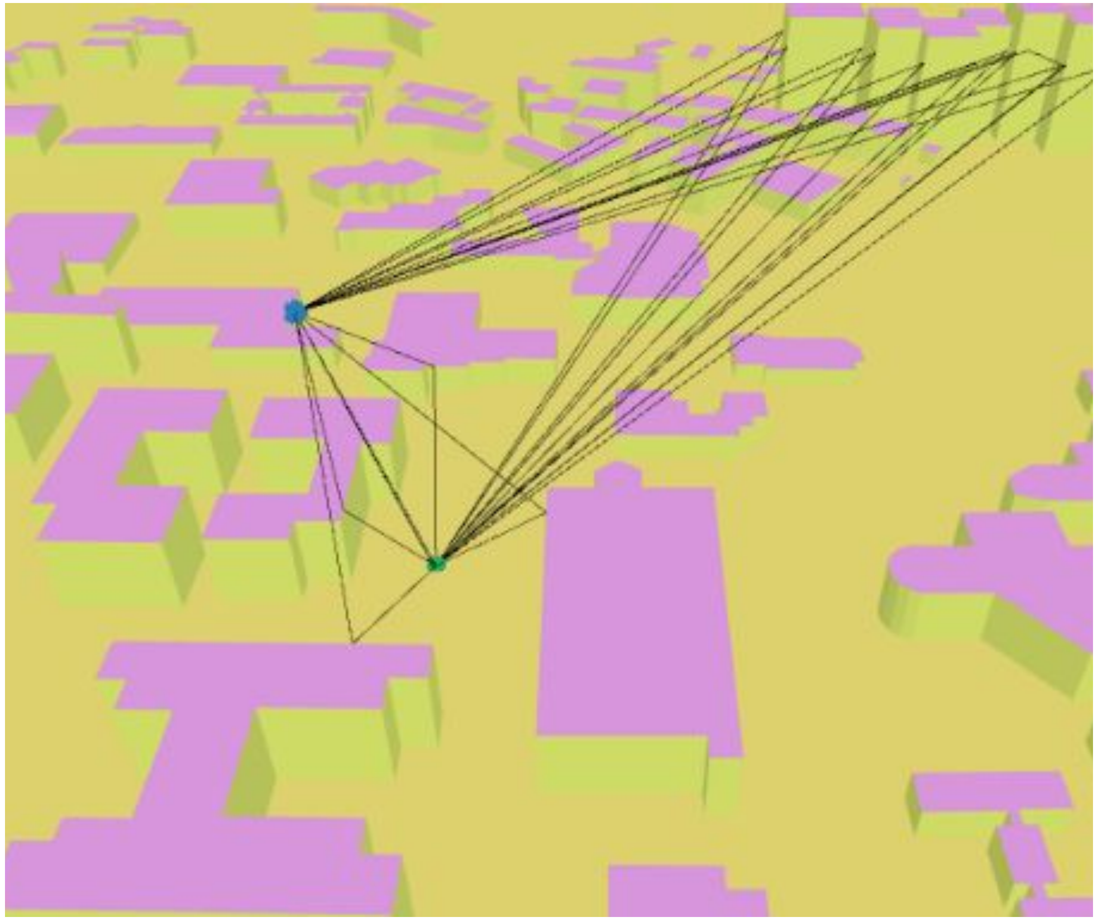
- **Integrated research platform**: It combines channel-, link-, and system-level simulation capabilities with machine learning support



courtesy : Sionna Documentation

What is Sionna?

- **Open-source** Wireless Communication Simulation Framework
- Built upon **TensorFlow**, designed for developing, analyzing, and validating wireless communication algorithms
- Particularly suited for research and development in modern wireless standards such as **5G/6G**



Video : https://youtu.be/cYUNE4i4Q4E

Simulation Accuracy

1. **Digital Twin fidelity**: Research comparing Sionna to Wireless InSite (WI) and real-world data from the FLASH dataset shows that Sionna's accuracy generally improves as the fidelity of the digital twin increases.

2. **LOS vs NLOS scenarios**: Sionna's performance varies between Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) scenarios, with accuracy trends slightly outperforming WI in certain parameters.

3. **Beam selection accuracy**: When evaluating the top 10 beams, Sionna's accuracy in matching real-world data ranges from 54% to 82% depending on the simulation fidelity.

4. **Comparison metrics**: Various metrics such as Magnitude Difference (MD), Cosine Similarity (CS), and Normalized Discounted Cumulative Gain (NDCG) show high similarity between Sionna and other simulators, particularly for higher-fidelity simulations.

5. and many other ongoing development: As an actively developed tool, Sionna's accuracy is likely to improve over time, with future extensions such as integrated ray tracing promising even more precise simulations

Application Scenario Example

For first two : **Digital Twin fidelity** and **LOS vs NLOS scenarios** we could show some applications scenario

Background & Motivation

UAV(Unmanned aerial vehicle) as aerial base station

⇨ 3D spatial air-to-ground communication

Current limitation：

- Traditional communication model is for simple environment
- Mobility and obstacle in UAV communication scenario

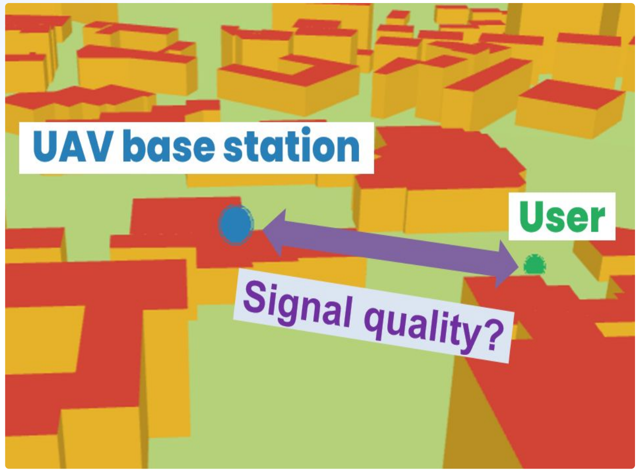
⇨ The estimation of signal quality becomes more complex and challenging

Objective : To understand the signal quality for users in different areas within an air-to-ground communication system

Signal Quality Estimation Framework Based on Large Language Model

- Fine-tuning the Large Language Model (LLM)
- Enabling users to understand the communication environment through text-based queries and answers
- Applying and validating this framework in NYCU campus

What we do? – 3D Channel GPT



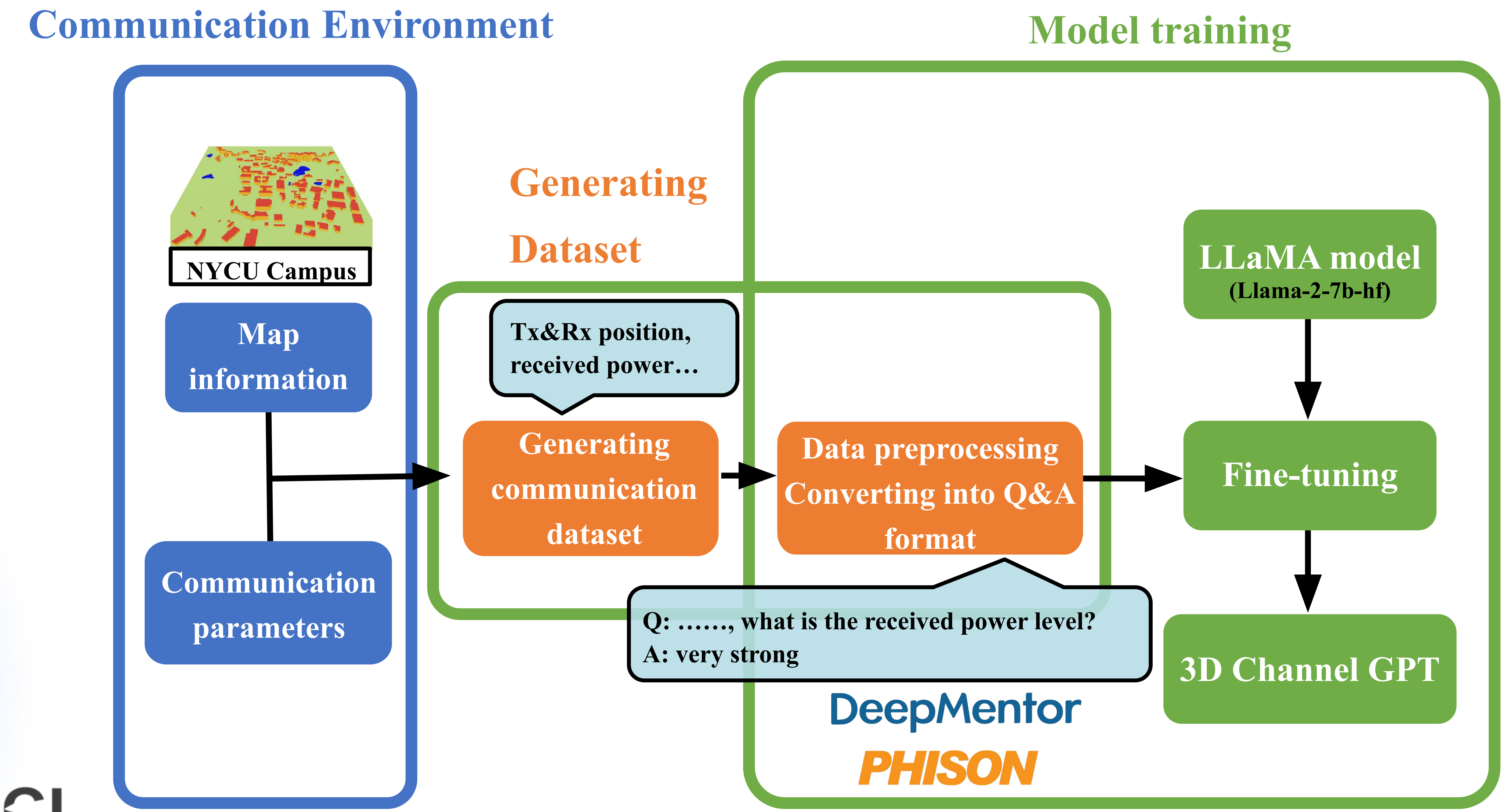
Input the 3D spatial position information of base stations and ground users into the AI model

The model outputs the estimated signal quality results.

generate → ……, what is the received power level? → input → 3D Channel GPT → output → Very strong

- We create **3D Channel GPT**, which provides **user-friendly Q&A dialogue service** to assess signal quality in **site-specific** 3D air-to-ground communication by extending DeepMentor solution.

3D Channel GPT Framework



3D Channel GPT : Workflows

Environment and dataset construction

- Radio Map Simulation
- Dataset Collection
- Dataset Preprocess

Model training

- LLaMA
- 3D Channel GPT

Model validation

- Case 1
- Case 2
- Conclusions

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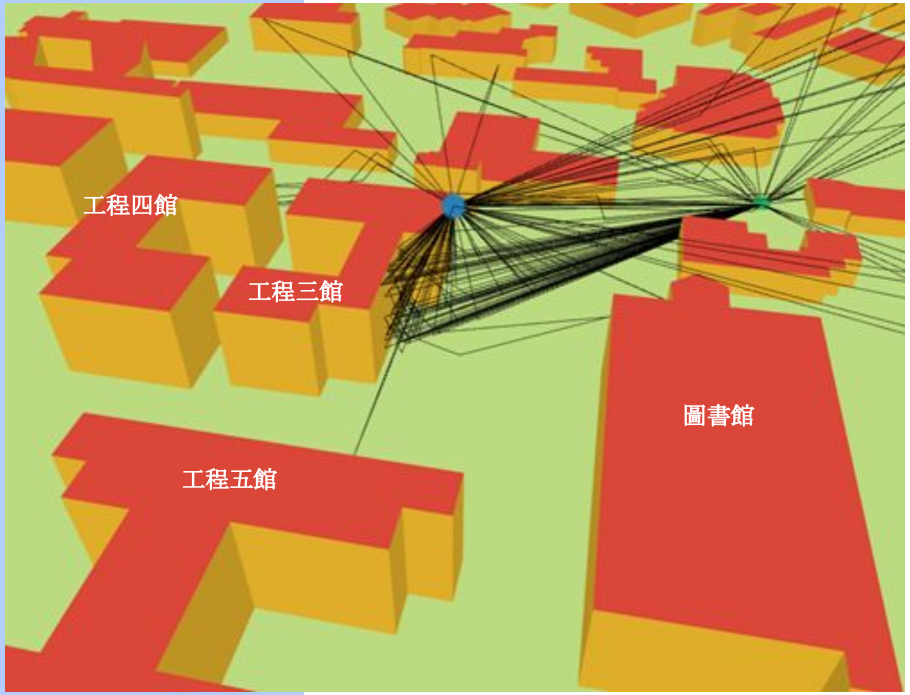
Environment and dataset construction

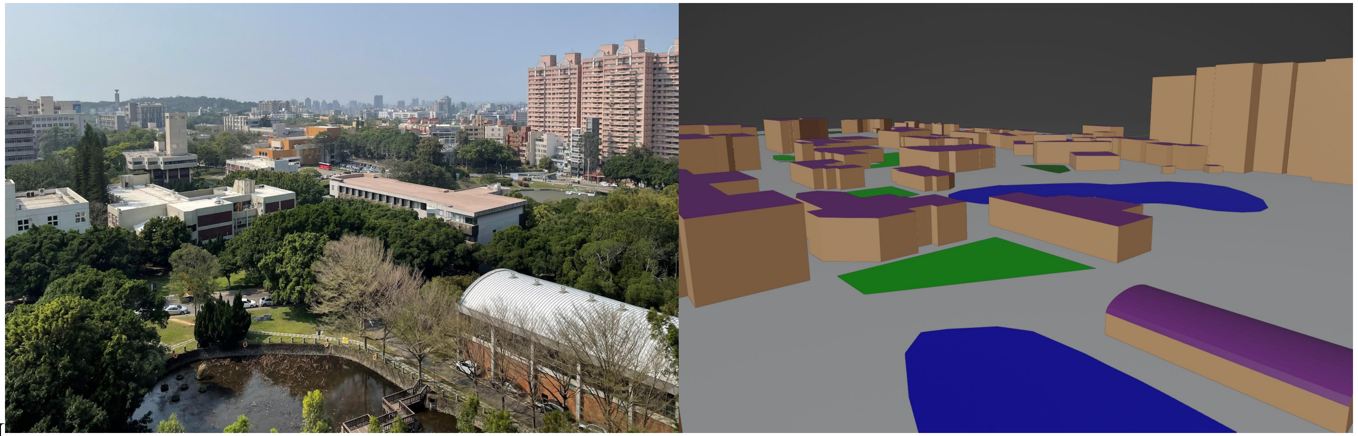
The First Open Data Generated Radio Map@ NYCU Campus

	Traditional Method	Our Method	
Map information	Required On-Site Measurements	Open-Source Information	✅
Ray tracing communication simulation	$$$$	Free (Open-Source)	✅
AI support	Low	High	✅

Our team has developed a simulated communication environment for NYCU campus by integrating open-source map data and employing Ray tracing technology.



▲ Simulation of the Communication Environment of NYCU Campus using Ray Tracing



▲ Comparison between NYCU Real World and Rendered Scenes

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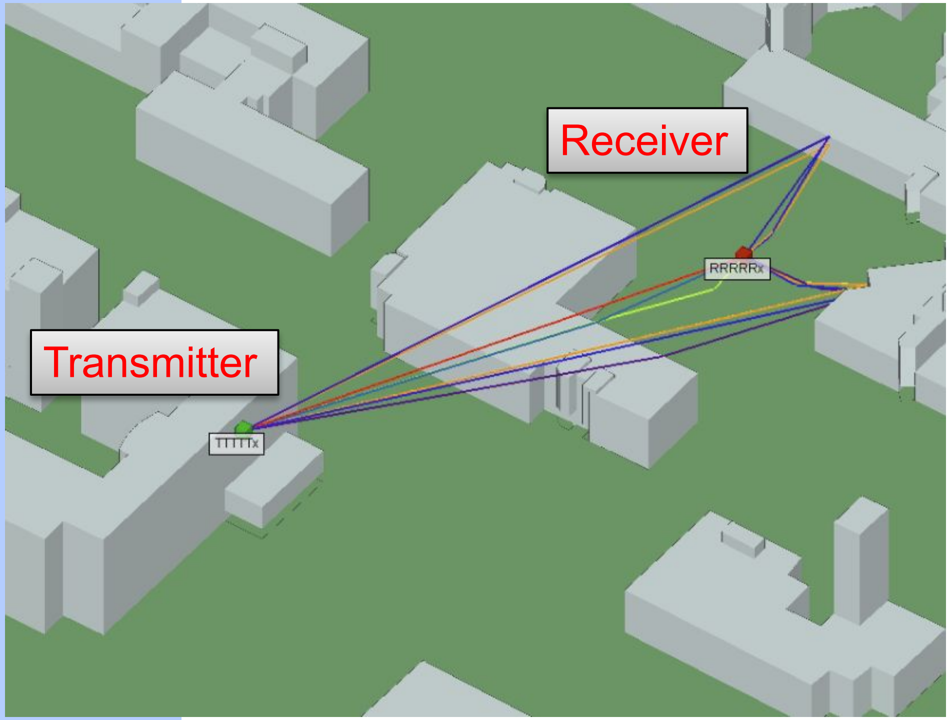
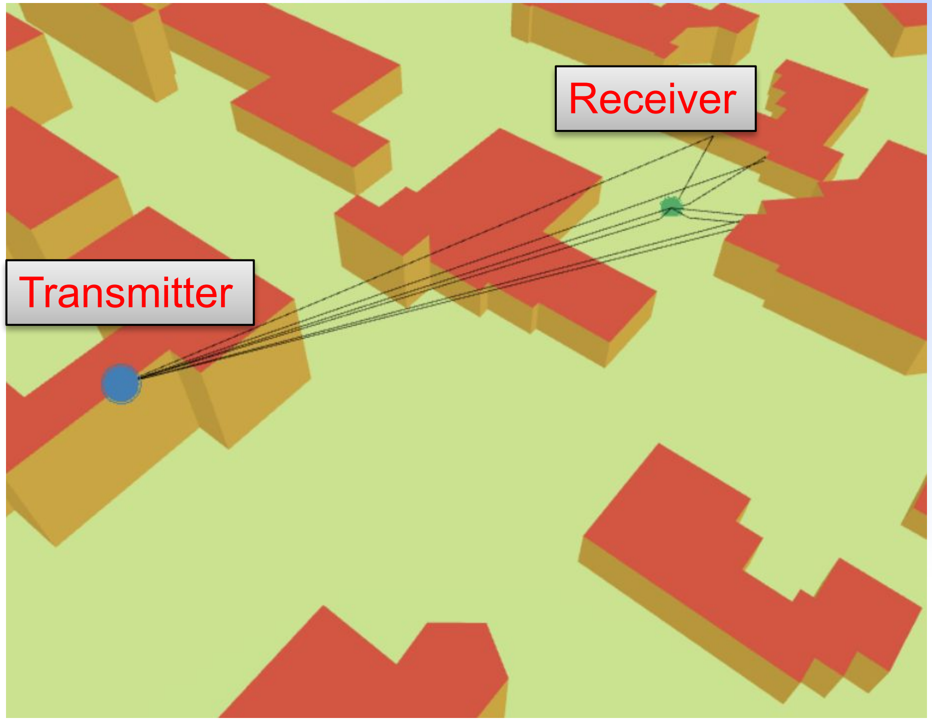
Comparison : Traditional Radio Map vs. Our Approach



▲ Simulation of Traditional Method



▲ Simulation from our Method

	Traditional Method	Our Method
Path loss	84.346 dB	84.377 dB
Computing time	50.506 s	0.268 s

Similar Results

Faster Computing Time

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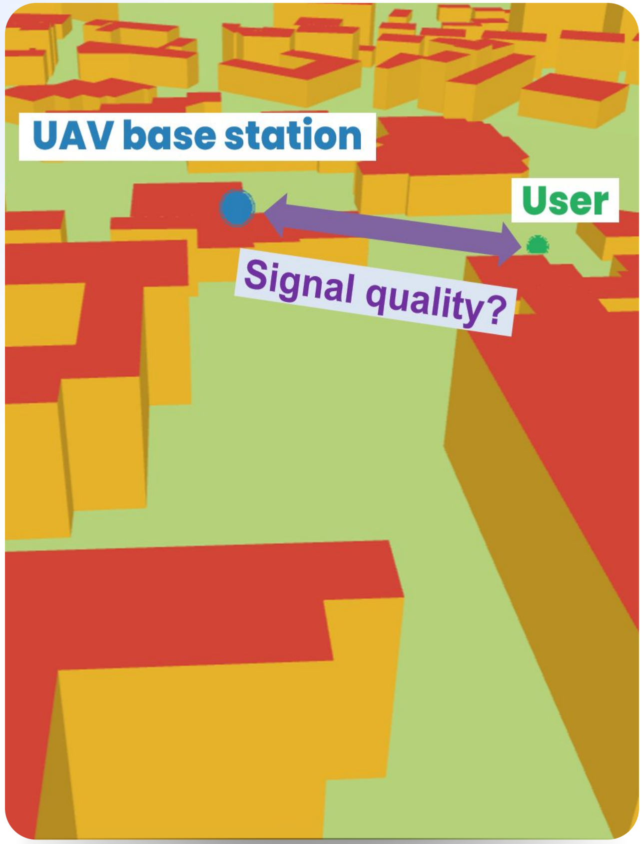
Environment-Aware Radio Signal Map by Ray Tracing



▲ Wireless Communications' Simulation Parameters based on UAV and User Locations

Wireless communication parameter setting

Parameters	Description
UAV Position	(0, 0, 100)
Carrier Frequency	2.65 GHz (4GLTE band 7)
User Position	Random

⇩

Randomly Sample 10,000 Data Points

⇨

Record

User Location

Distance (UAV-User)

LoS / NLoS

User's Received Power

Classify Radio Signal Strength to Signal Quality Opinion

Original Data

Base_station_ID	Tx_x	Tx_y	Tx_z	Rx_x	Rx_y	Rx_z	Distance	Frequency	LOS_Flag	Transmit power (dBm)	Received power (dBm)
Base_Station_UAV	0	0	100	-183.333	7.265218	1.5	208.2448	2.65E+09	1	0	-87.2452

	Path Loss	**Signal quality opinion**
Signal Quality Classification	PL ≦ 88	Very strong
	89 ≦ PL ≦ 92	Strong
	93 ≦ PL ≦ 96	Fair
	97 ≦ PL ≦ 100	Weak
	101 ≦ PL	Very weak
	No signal Received	No signal Received

Transfer Ray Tracing Signal to Q&A Syntax

Original Data

Base_station_ID	Tx_x	Tx_y	Tx_z	Rx_x	Rx_y	Rx_z	Distance	Frequency	LOS_Flag	Transmit power (dBm)	Received power (dBm)
Base_Station_UAV	0	0	100	-183.333	7.265218	1.5	208.2448	2.65E+09	1	0	-87.2452

Classify Radio Signal Strength to Signal Quality Opinion

Q&A Syntax

Question (Input)	**Answer (Output)**
In wireless communication environment, the base station is positioned at (X,Y,Z)=(0,0,100), and the receiver is at (X,Y,Z)=(-183,7,1). What is the received power level?	**very strong**

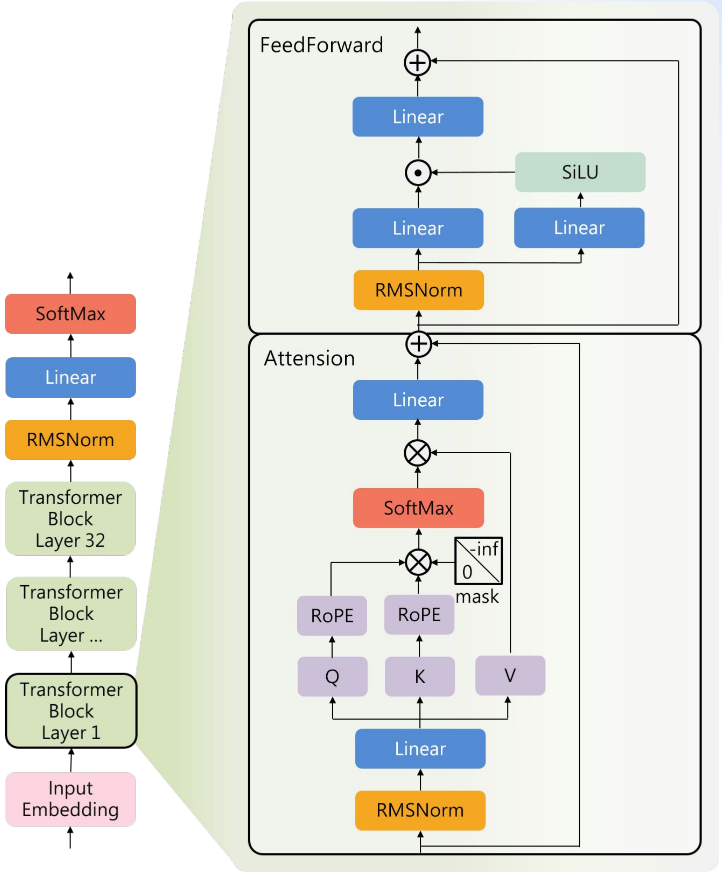
Model Training

LLaMA2 (Large Language Model Meta AI)

- **Meta's Open-Source Large Language Model (LLM)**
- **Foundation Language Model**

	Training Data	Params	Context Length	GQA	Tokens	LR
Llama 1	*See Touvron et al. (2023)*	7B	2k	✗	1.0T	3.0×10^{-4}
		13B	2k	✗	1.0T	3.0×10^{-4}
		33B	2k	✗	1.4T	1.5×10^{-4}
		65B	2k	✗	1.4T	1.5×10^{-4}
Llama 2	*A new mix of publicly available online data*	7B	4k	✗	2.0T	3.0×10^{-4}
		13B	4k	✗	2.0T	3.0×10^{-4}
		34B	4k	✓	2.0T	1.5×10^{-4}
		70B	4k	✓	2.0T	1.5×10^{-4}

▲ Comparison table outlining the differences between LLaMA1 and LLaMA2 models [1]

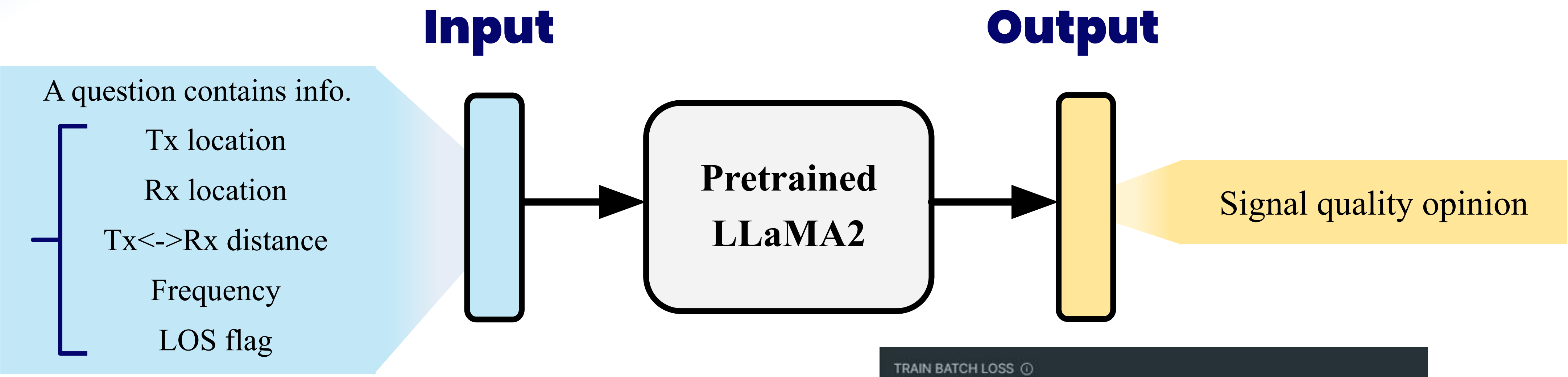


▲ Architecture diagram of the LLaMA2 model

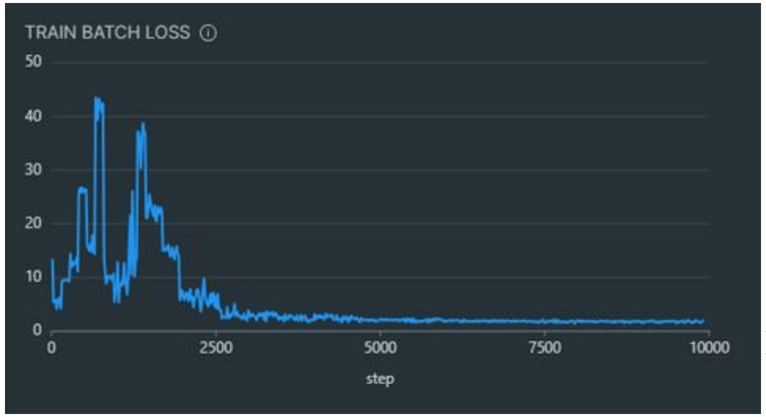
- **Increased Training Data by 40%**
- **Utilized Grouped-query attention (GQA) to accelerate inference**
- **Implemented RLHF (reinforcement learning from human feedback) in Llama2-chat models to enhance model robustness.**

[1] H. Touvron et al., "Llama 2: Open foundation and fine-tuned chat models," arXiv preprint arXiv:2307.09288, 2023.

Fine-tuning : LLaMA2 to 3D Channel GPT



- **99% Data is used for Finetuning**
- **1% Data is allocated for Validation**



Vertical (Y-axis): Training loss

Horizontal (X-axis): Training steps

▲ Training Loss Convergence Curve for the Model

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Model Validation

Case 1 : Single Base Station Scenario

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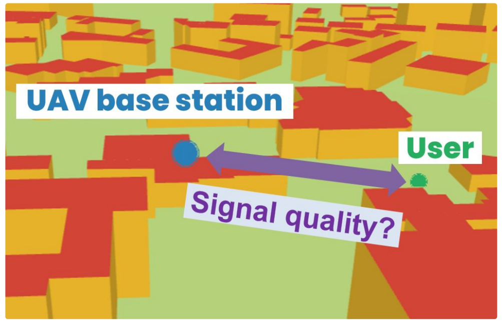

generate → ……, what is the received power level?

input → **3D Channel GPT**

output → Very strong

- **Randomly selecting 100 data points yields an accuracy of 84%**

⇨ **"Evaluating the effectiveness of LLM model in wireless communication scenarios."**

Input Text (tokenization max length setting may tr...	Target Text	Predicted Text
Question: In wireless communication environment, t **Answer :**	strong	fair
Question: In wireless communication environment, t **Answer :**	strong	strong
Question: In wireless communication environment, t **Answer :**	fair	fair
Question: In wireless communication environment, t **Answer :**	no signal received	no signal received
Question: In wireless communication environment, t **Answer :**	very strong	very strong
Question: In wireless communication environment, t **Answer :**	fair	fair

▲ Comparison of the actual results and model output

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Case 1 : Single Base Station Scenario

Result Comparison : Model Prediction vs. Actual Results

User Location	Input Text (tokenization max length setting may r...	Target Text	Predicted Text	
(-226,365,1)	**Question:** In wireless communication environment, the **Answer :**	strong	fair	Fail
(232,-146,1)	**Question:** In wireless communication environment, the **Answer :**	strong	strong	Correct
(-594,-215,1)	**Question:** In wireless communication environment, the **Answer :**	fair	fair	Correct
(-213,-351,1)	**Question:** In wireless communication environment, the **Answer :**	no signal received	no signal received	Correct
(-17,67,1)	**Question:** In wireless communication environment, the **Answer :**	very strong	very strong	Correct
(-559,-317,1)	**Question:** In wireless communication environment, the **Answer :**	fair	fair	Correct

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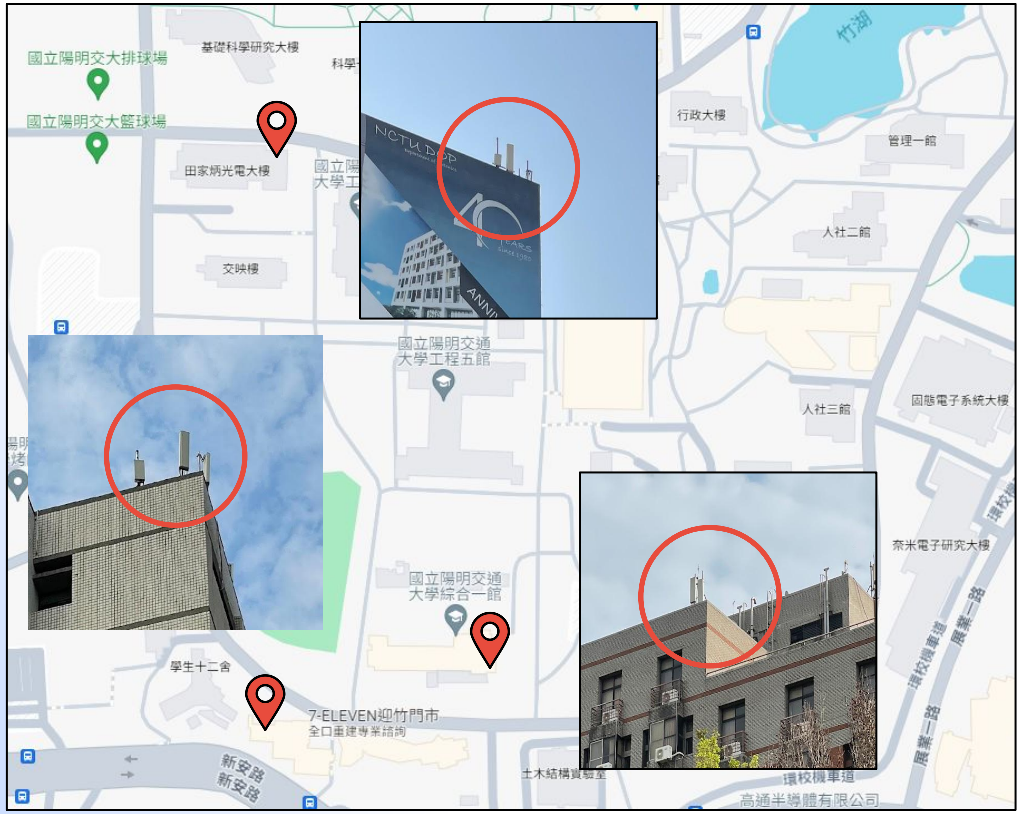
Case 2 : CHT BSs Signal Quality Opinion by 3D Channel GPT

Objective: Estimating signal quality with multiple base stations in the campus environment of NYCU Campus



▲ Actual deployed locations of Chunghwa Telecom base stations in the Guangfu Campus of Yang Ming Chiao Tung University

Expected Results

Record

- User Location
- BSs (A/B/C) Location
- User - BSs Distance
- Signal Quality of User Specific Location from BSs

(Q&A Format 1)

……, which base station's signal is the strongest?

base station B

(Q&A Format 2)

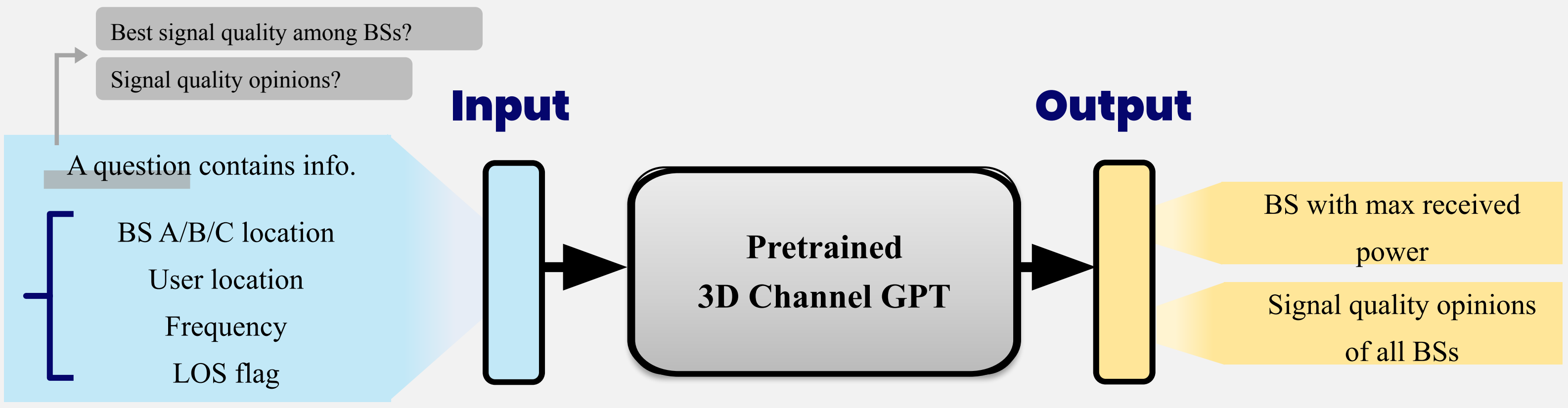
…… Please answer the received power level of all base stations.

base station A : no signal received
base station B : strong
base station C : very weak

Case 2 : CHT BSs Signal Quality Opinion by 3D Channel GPT

Wireless communication parameter setting

Parameters	Description
BS A Position	(-150, -330, 40)
BS B Position	(0, -275, 40)
BS C Position	(-150, 50, 40)
Carrier Frequency	2.65 GHz (4GLTE band 7)
User Position	Random



99%Training
1%Validation

Randomly sample 10,000 data

Conversion to 20,000 Q&A format

(Format 1 10,000 data)
(Format 2 10,000 data)

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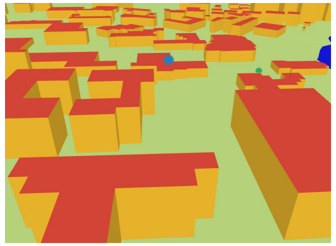
Case 2 : CHT BSs Signal Quality Opinion by 3D Channel GPT



generate

Q ……, which base station's signal is the strongest?

Q2 …… Please answer the received power level of all base stations.

input

3D Channel GPT

output

A1 base station B

A2 base station A : no signal received
base station B : strong
base station C : very weak

- (Q&A Format 1)Randomly sample 100 data, resulting in an accuracy of 67%
- (Q&A Format 2)Randomly sample 100 data, resulting in an accuracy of 62%

(Due to the increased complexity of the scenario, the accuracy has decreased compared to Case 1.)

⇨ Furtherly extend the capabilities of 3D Channel-GPT model through users and Multiple base stations through simple Q&A interactions

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Conclusions

- We(NYCU ICCLab) creates 3D Channel GPT (Generative Pretrained Transformer), achieving signal quality opinion score up to 84% accuracy with the help of DeepMentor solution.

- Develop a methodology to generate the first open data radio signal map @ NYCU campus, which can be extended further for 3D+Radio dataset in other cities.

- 3D Channel GPT provides user-friendly Q&A dialogue service for assessing signal quality in site-specific 3D air-to-ground communication.

However underlying **Challenges** exists….

1. **Stochastic vs Deterministic Models**:

   While supporting 3GPP 38.901 channels, Sionna's accuracy in NLOS scenarios still trails specialized tools like Wireless InSite by 15-20% in beam selection tests

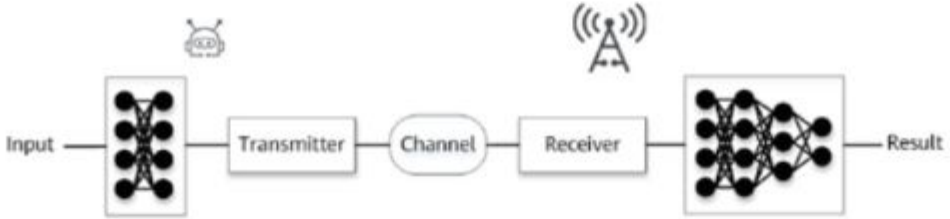
2. **Quantization Effects**:

   Hardware implementation mismatches emerge from ideal simulations vs actual RF impairments

3. **Mobility Handling**:

   Simulating high-velocity scenarios (e.g., >500 km/h) strains current ray tracing capabilities

Learning Curve



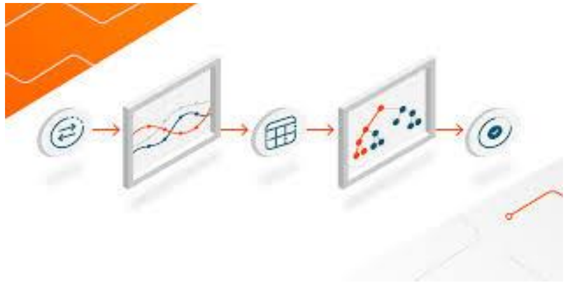
source : beyond traditional communications, Huawei Research

1. Cross-Disciplinary Expertise

   Requires simultaneous mastery of:

   - TensorFlow/Keras for neural network integration
   - Communication theory (LDPC, MIMO, OFDM)
   - Ray optics for propagation modeling

TensorFlow



Learning Curve

2. API Complexity

The framework's flexibility introduces challenges in:

- **Debugging gradient** flows through hybrid AI/DSP pipelines
- **Customizing lower PHY** components while maintaining differentiability

```
batch_size = 1024
n = 1000 # codeword length
k = 500 # information bits per codeword
m = 4 # bits per symbol
snr = 10 # signal-to-noise ratio

c = Constellation("qam",m,trainable=True)
b = BinarySource()([batch_size, k])
u = LDPC5GEncoder (k,n)(b)
x = Mapper (constellation=c)(u)
y = AWGN()([x,1/snr])
llr = Demapper("app", constellation=c)([y,1/snr])
b_hat = LDPC5GDecoder(LDPC5GEncoder (k, n))(llr)
```

⇩

```
c = Constellation("qam",m,trainable=True)
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x = Mapper (constellation=c)(u)
y = AWGN()([x,1/snr])
llr = NeuralDemapper()([y,1/snr])
b_hat = LDPC5GDecoder(LDPC5GEncoder (k, n))(llr)
```

Customization :
replacing Demapper with NeuralDemapper

Operational Constraints

1. Version Compatibility: Strict requirements for Python 3.8-3.12 and TensorFlow 2.14-2.19 create dependency conflicts
2. Multi-GPU Scaling: Distributed training needs careful resource management for large batch sizes
3. Reproducibility: Differences in GPU architectures (Ampere vs Hopper) affect benchmark consistency

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NCTU Department of Electrical and Computer Engineering

6G Physical-Layer Research Tools
NVIDIA Sionna: An Open-Source Library

Presenter：Chia-Chuan Chiu

Advisor：Li-Chun Wang

Class GitHub: https://github.com/NYCU-ICCLab/sionna_introduction
NVIDIA website: https://developer.nvidia.com/sionna
Sionna official tutorial: https://nvlabs.github.io/sionna/index.html
Sionna GitHub: https://github.com/NVlabs/sionna

Key Features of Sionna

- **Modular & Flexible Design**
  - Modular architecture that can be easily customized or extended.
  - Allows quick prototyping of complex communication systems.
- **Integration with Deep Learning**
  - Parameters are constructed using TensorFlow
- **High Computational Efficiency**
  - Accelerated by GPU computing

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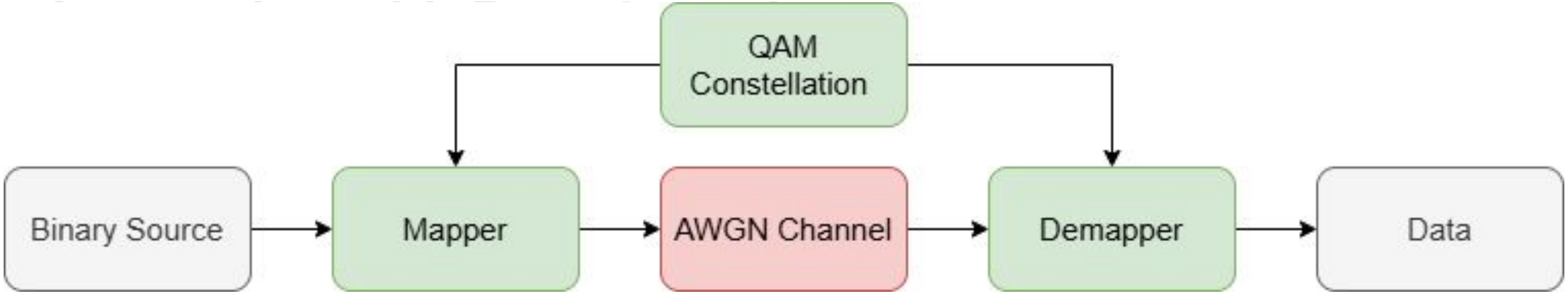

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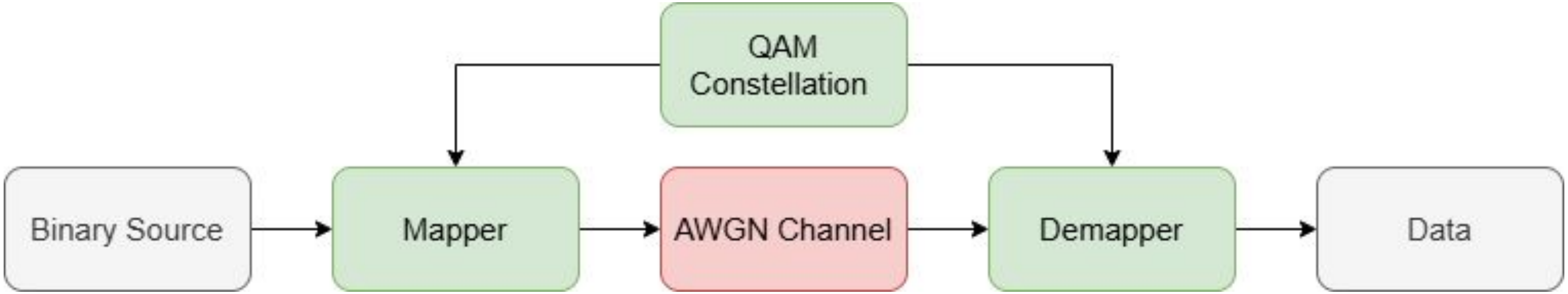

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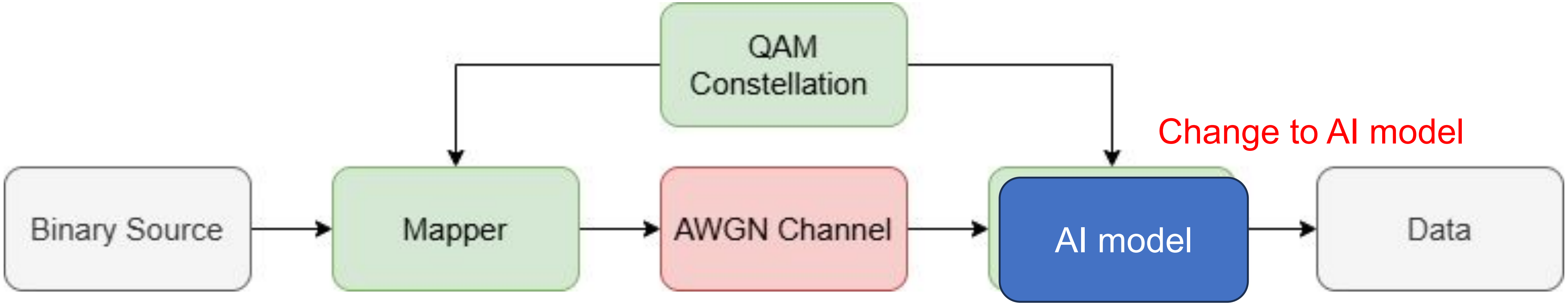

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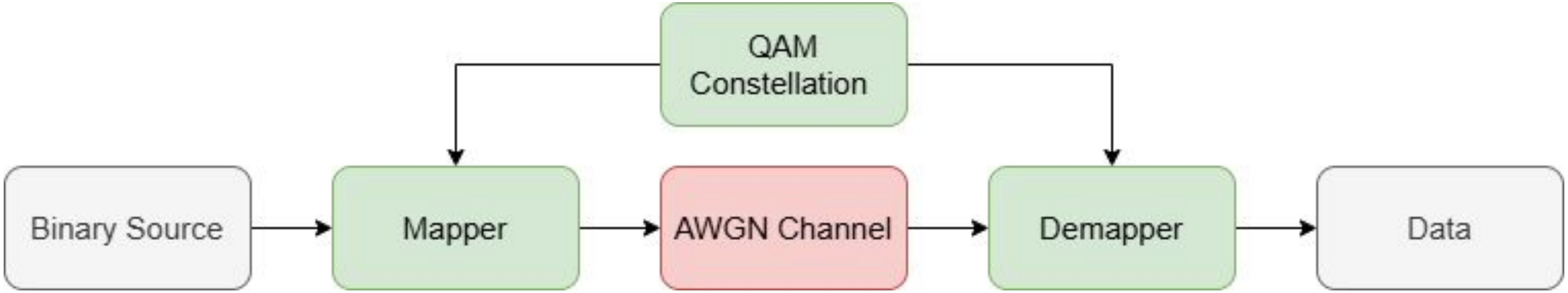
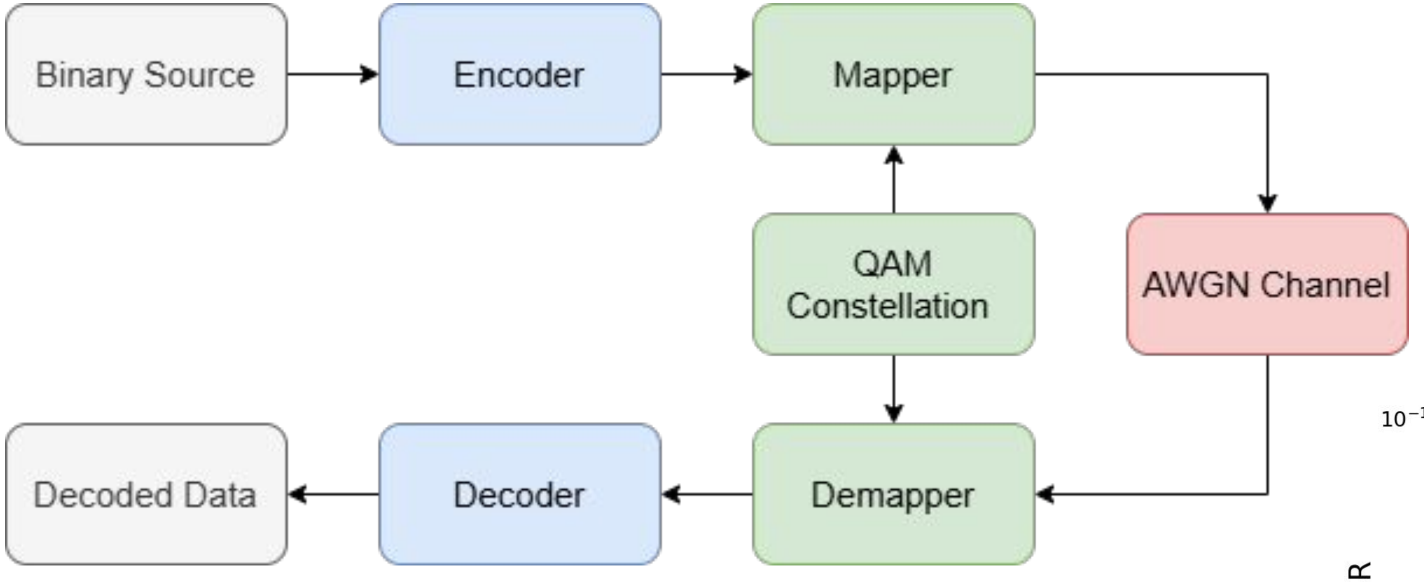
Basic Usage of Sionna

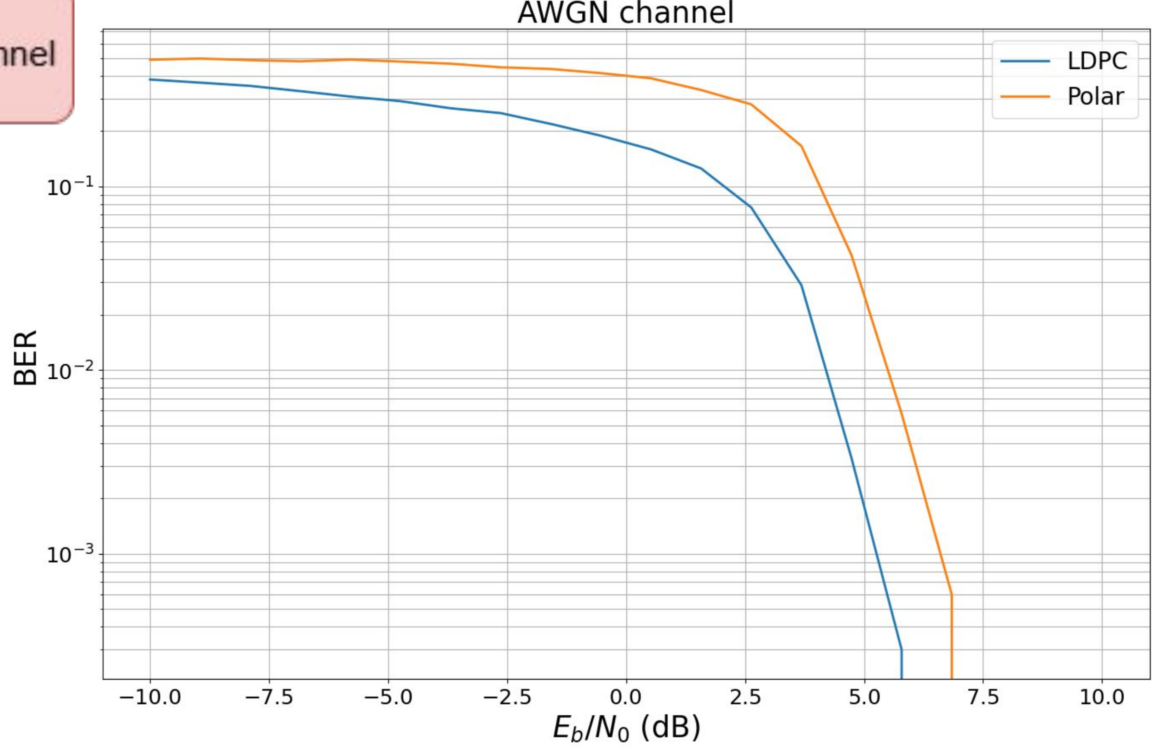


https://github.com/NYCU-ICCLab/sionna_introduction/blob/main/sample_code/Demo_sionna_basic.ipynb

Case 1 : System Performance Evaluation

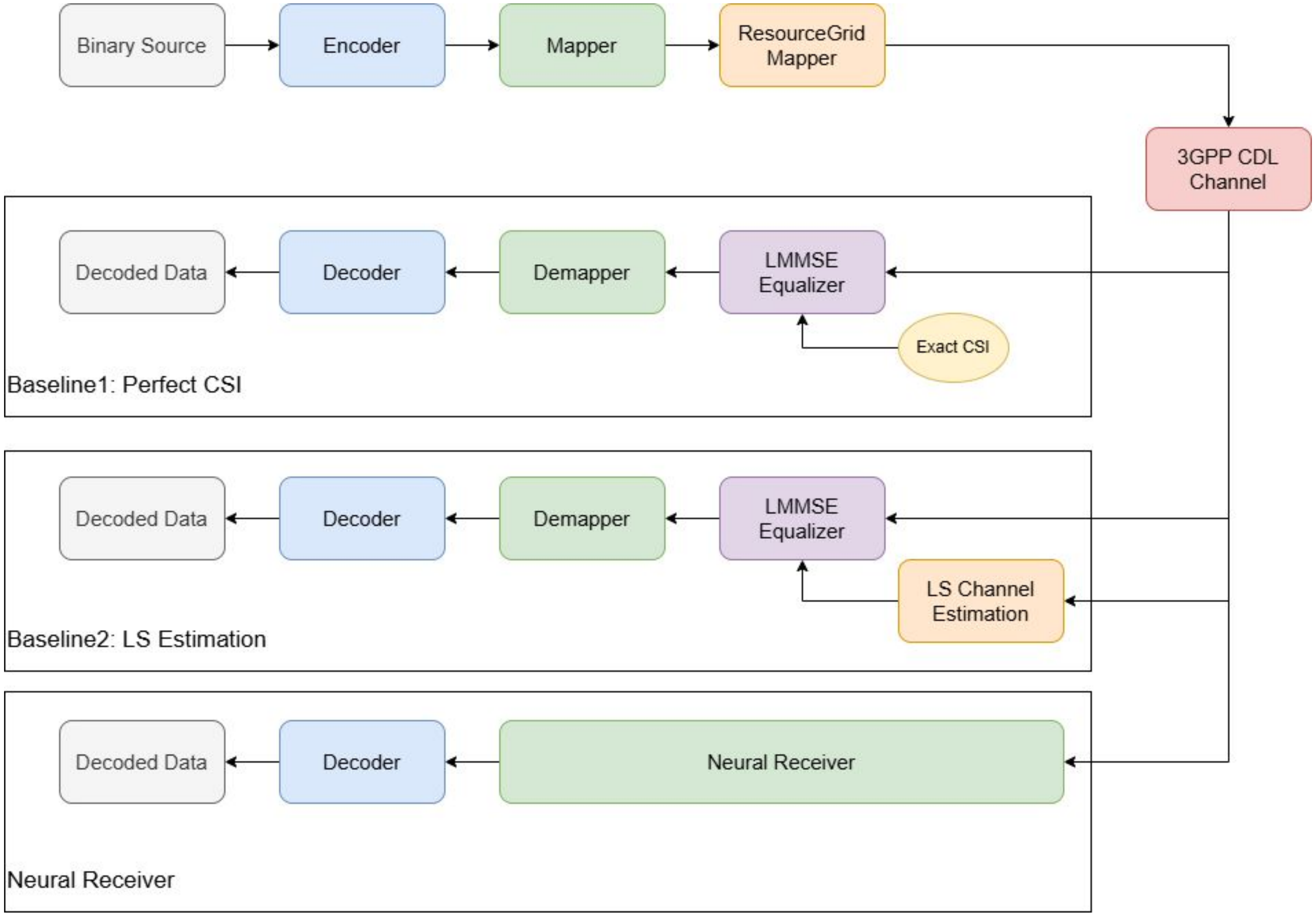


Channel coding comparison: LDPC vs Polar



https://github.com/NYCU-ICCLab/sionna_introduction/blob/main/sample_code/Demo_LDPC_vs_Polar.ipynb

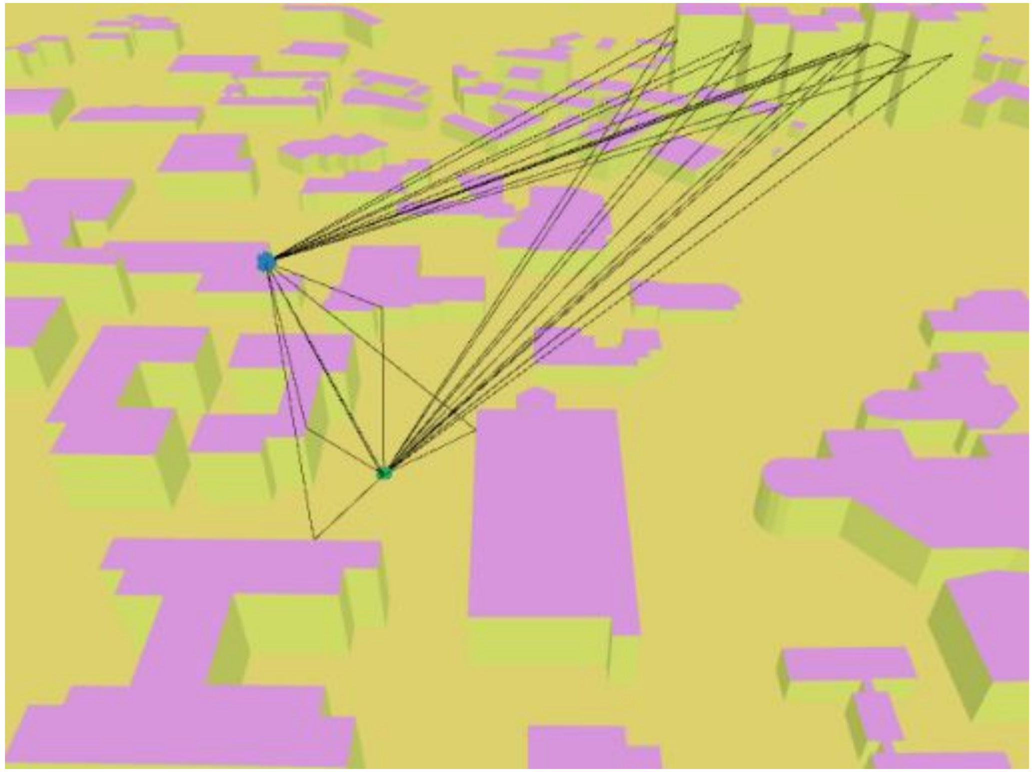
Case 2 : Neural Receiver

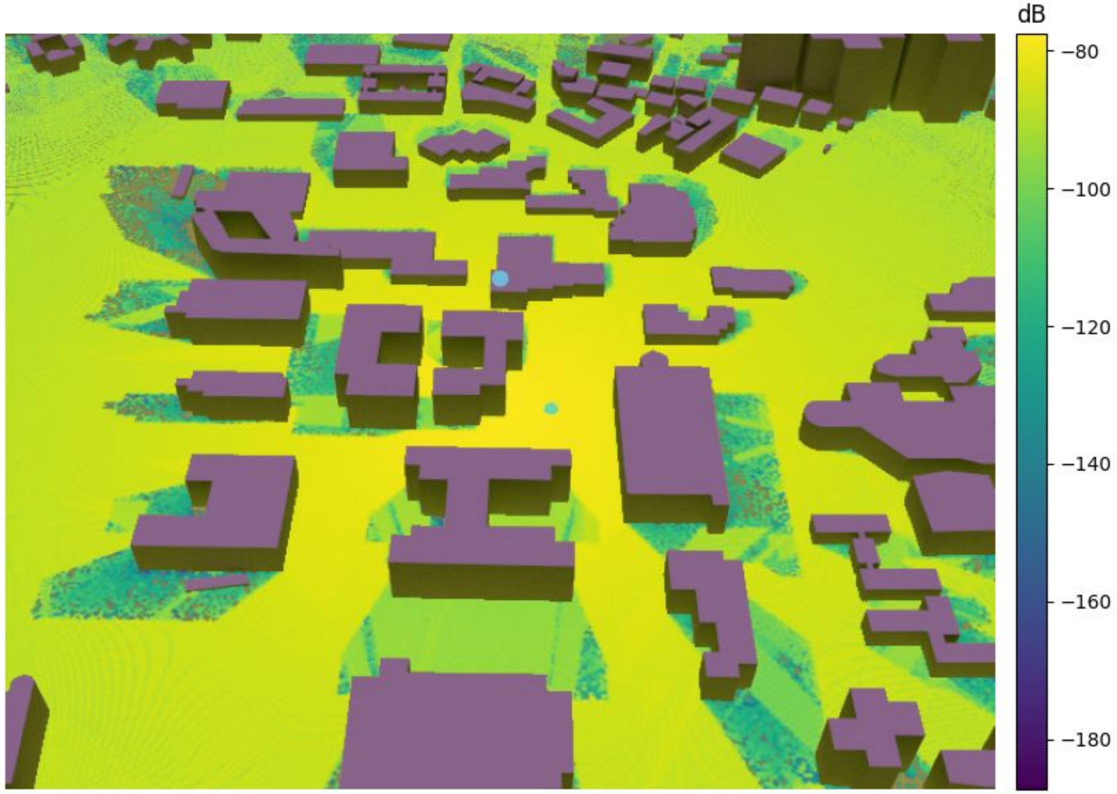


https://github.com/NYCU-ICCLab/sionna_introduction/blob/main/sample_code/Demo_neural_receiver.ipynb

Case 3 : Ray Tracing

Ray tracing simulation in NYCU campus





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Thank You

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