ONBOARD TERRAIN CLASSIFICATION VIA STACKEDINTELLIGENT METASURFACE-DIFFRACTIVE DEEPNEURAL NETWORKS FROM SAR LEVEL-0 RAW DATA

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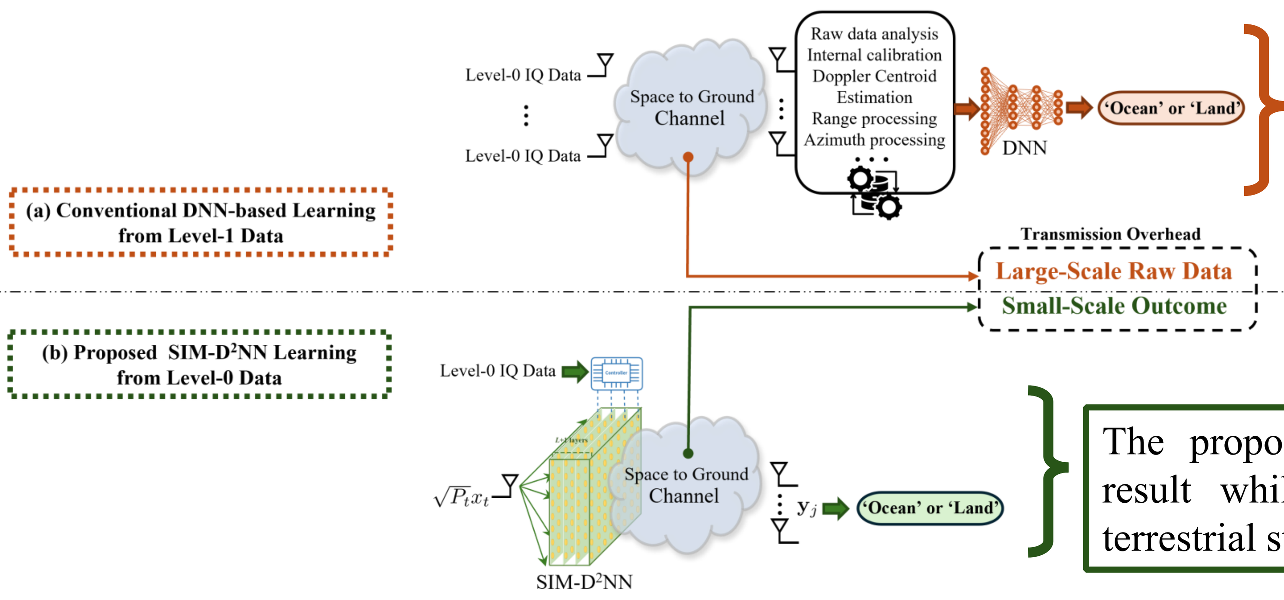
Motivation & Challenges



The conventional pipelines rely on complex algorithms for high-level SAR products (e.g., SLC), which inevitably needs a large amount of transmission resource.

The proposed pipelines deduce the classification result while transmitting the raw data back to terrestrial station.

Figure 1: Comparison of processing progress.

◆**How do we design the SIM-D²NN to achieve real-time terrain classification?**

Challenges:

- How to optimize the phase configurations at each metasurface layer?
- How to deduce the classification result from the received signal at the terrain station?
- How to tackle the noisy level-0 raw I/Q data[1]?

[1]The S1 level-0 raw data used for training is downloaded from the Copernicus browser (https://browser.dataspace.copernicus.eu).

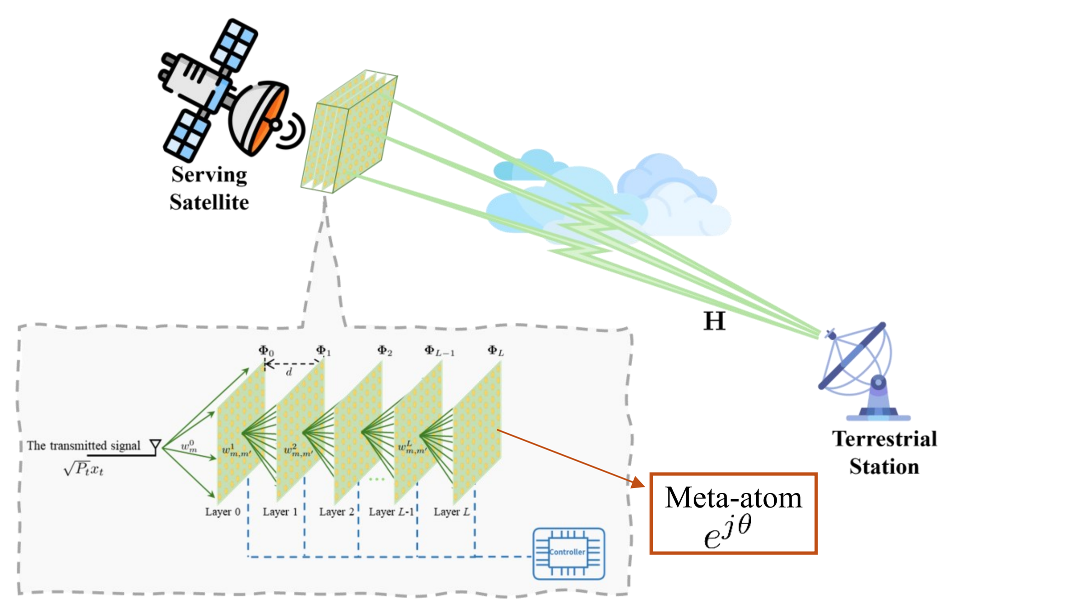


Figure 2: The overview of the satellite-to-ground transmission system.

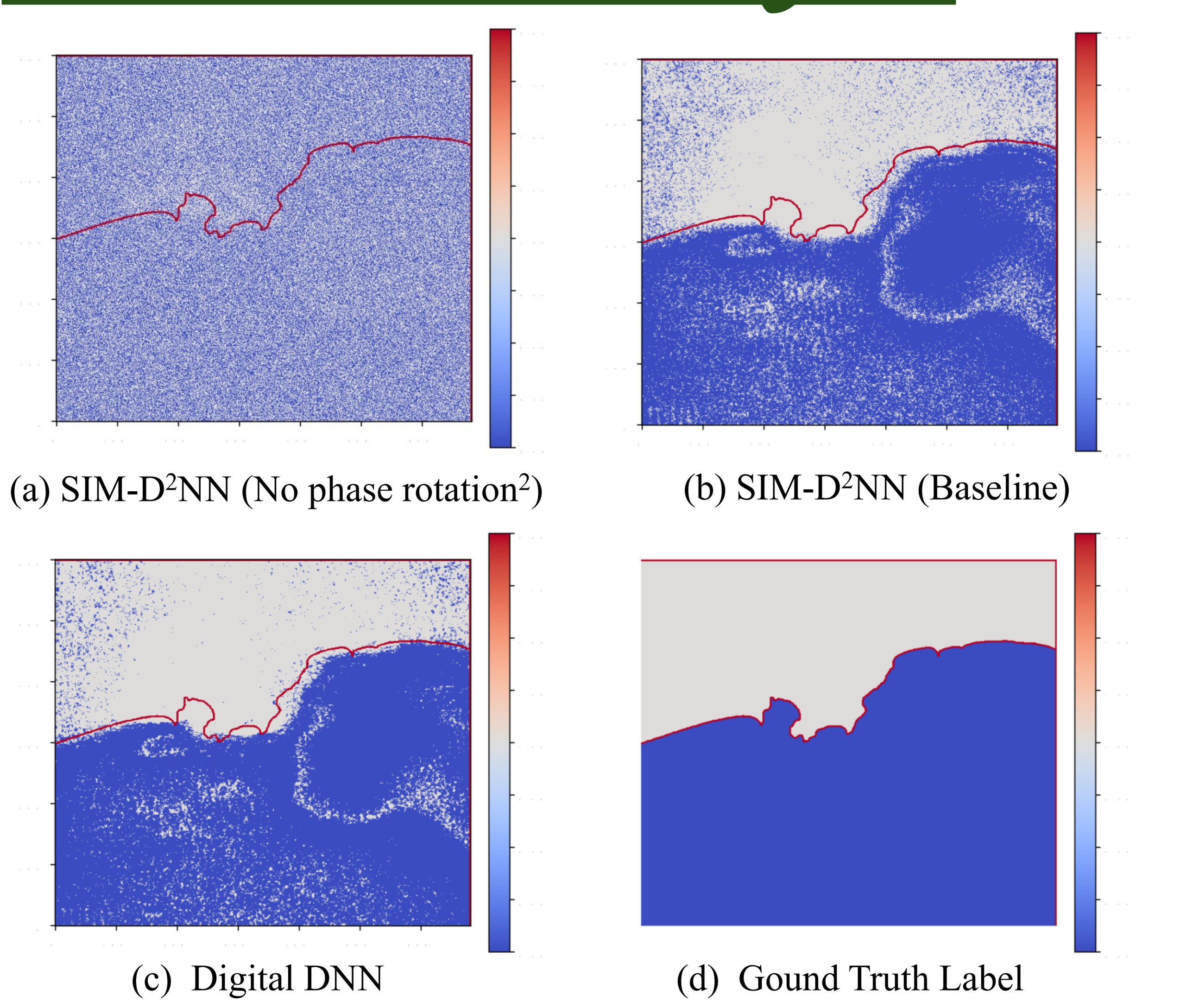
What is SIM-D²NN?

- Multiple-layer stacked intelligent metasurface; (Mimic the structure of DNN)
- Signal transmitted from the satellite to the station via SIM; (Feedforward in DNN)
- The phase configurations θ of meta-atoms at each layer; (The learnable weights in DNN)

Why SIM-D²NN?

- **Offload the computation** (heavily rely on digital backends) into the natural signal propagation in wave domain;
- **Relieve the huge demand of transmission resources,** such as the bandwidth and the energy consumption;
- Achieve **real-time, in-orbit decision-making** for the terrain classification task in remote sensing applications.

Results & Analysis



(a) SIM-D²NN (No phase rotation[2]) (b) SIM-D²NN (Baseline)

(c) Digital DNN (d) Gound Truth Label

Figure 3: Comparison of the visualization results under different methods.

- Form (a), the inclusion of **phase rotation proves essential** for effectively learning from the IQ raw data;
- From (b) and (c), the analog SIM-D²NN achieves **similar results** to the digital DNN.

Table 1: Comparison of different scenarios on the S1 level-0 raw IQ dataset.

Ablation Setting	S1 Level-0 Raw IQ Dataset			
	Precision (%) ↑	**Recall (%) ↑**	**F1 Score (%) ↑**	**Overall Accuracy (%) ↑**
SIM-D²NN ($L=1$)	87.63	91.27	89.41	83.44
SIM-D²NN ($L=6$)	87.21	92.87	89.95	88.15
SIM-D²NN ($S=5\%$)	87.84	91.49	89.62	85.75
SIM-D²NN ($S=20\%$)	91.56	93.98	92.76	89.31
SIM-D²NN ($P_t=5$ dBm)	86.14	92.20	89.07	80.29
SIM-D²NN (No phase rotation)	62.09	78.54	69.35	54.97
SIM-D²NN (Baseline)	90.54	90.67	90.60	87.83
Digital DNN	*94.78*	*97.14*	*95.95*	*92.91*

Note: Our baseline SIM-D²NN uses $L=4$ layers, $P_t=20$ dBm, and $S=10\%$.

- Increasing the number of **Metasurface Layers** from L=1 to L=4, leading to an increase in precision score (87.63% to 90.54%);
- Omitting the **phase rotation** augmentation leads to a significant drop in recall score (78.54% to 90.67%);
- **Sampling** more training samples may achieve higher performance, such as the F1 score (89.62% to 92.76%);
- Reducing **transmit power** P_t from 20 dBm to 5 dBm degrades accuracy from 87.83% to 80.29%.

[2] The phase rotation is adopted for data augmentation, which can be modulated on the chip naturally as the carrier waves pass through the input layer.

Conclusion

- Develop a multi-layer, **SIM-D²NN** designed to **process S1 raw IQ data** for terrain classification;
- By harnessing the **inherent properties** of wave propagation through multiple layers to achieve high performance as around **90%**;
- **Reducing** the dependence on **digital processing** backends and **lowering the costs** associated with data transmission;
- Offering **faster, more efficient, and sustainable solutions** for remoting sensing applications.

Path Forward

- **Nonlinear Function:** Relying on specialized metasurface hardware, which is constrained to linear operations and limits the SIM-D2NN from performing critical nonlinear functions.
- **Time-varying wireless environment:** While we consider the noise and phase modulus constraints, real-word communication links might introduce more complex distortions, such as time-varying channels, imperfect channel information, and dynamic path loss.
- **Comprehensive remote sensing tasks:** Future work will try to expand on more remote sensing tasks and make the SIM-D2NN more generalized capability.

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