2D-RC: Two-Dimensional Neural Network Approach for OTFS Symbol Detection

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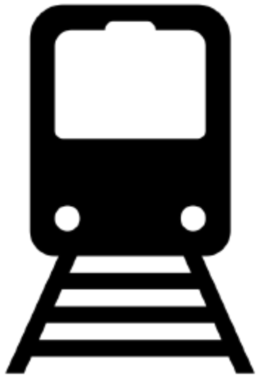
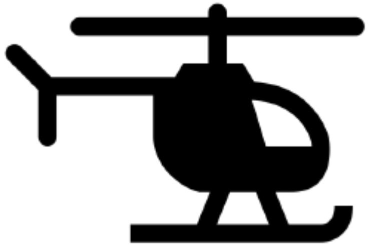
High Mobility Scenarios

- High mobility scenarios



High speed train

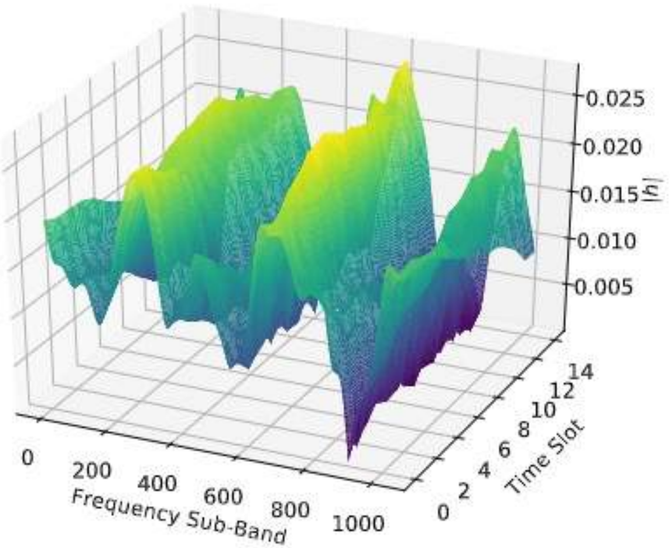


Aircraft-to-ground communication

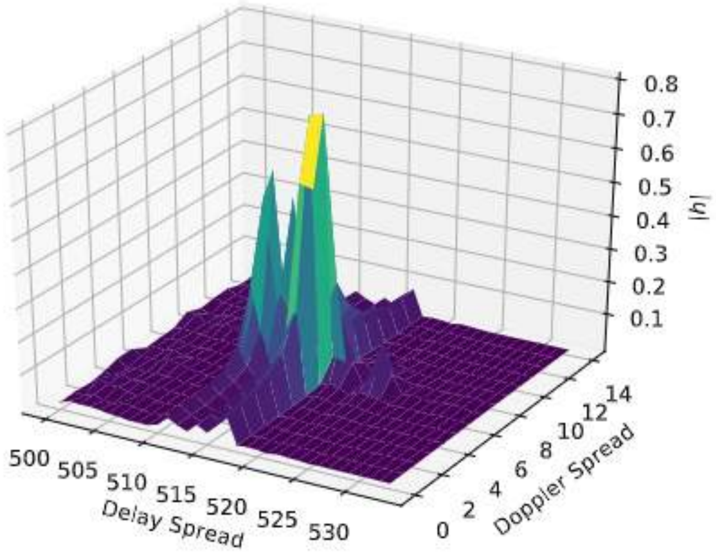
Unmanned aerial vehicle (UAV) communication systems

Orthogonal Time Frequency Space (OTFS)

- Orthogonal time frequency space (OTFS)
  - Transmit the information symbols in the delay–Doppler domain
  - Less channel variation in the delay–Doppler domain



Time-Frequency Channel Representation



Delay-Doppler Channel Representation

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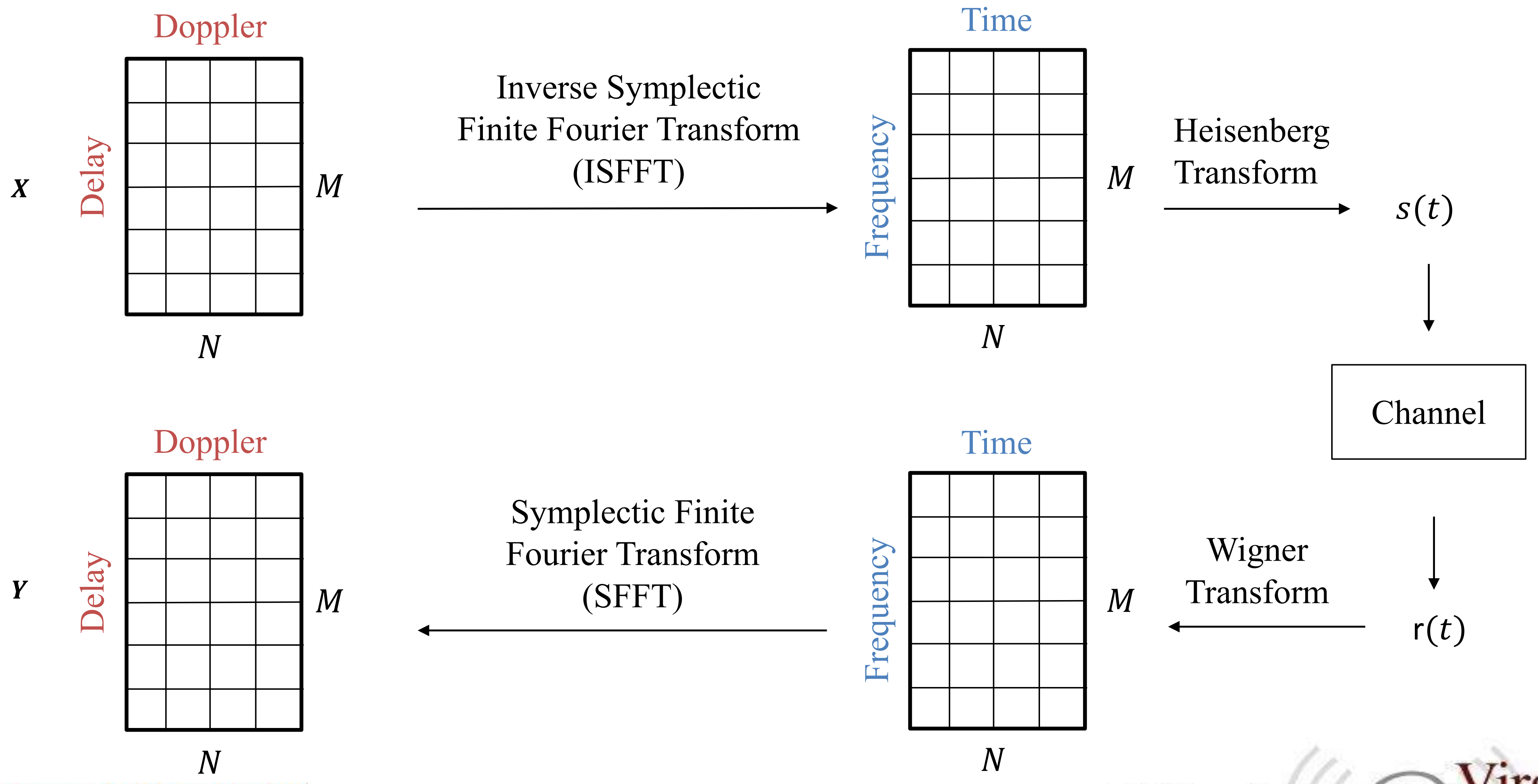
The Problem: Symbol Detection in the OTFS System



Existing Work for OTFS Symbol Detection

- Existing work for symbol detection in the OTFS system

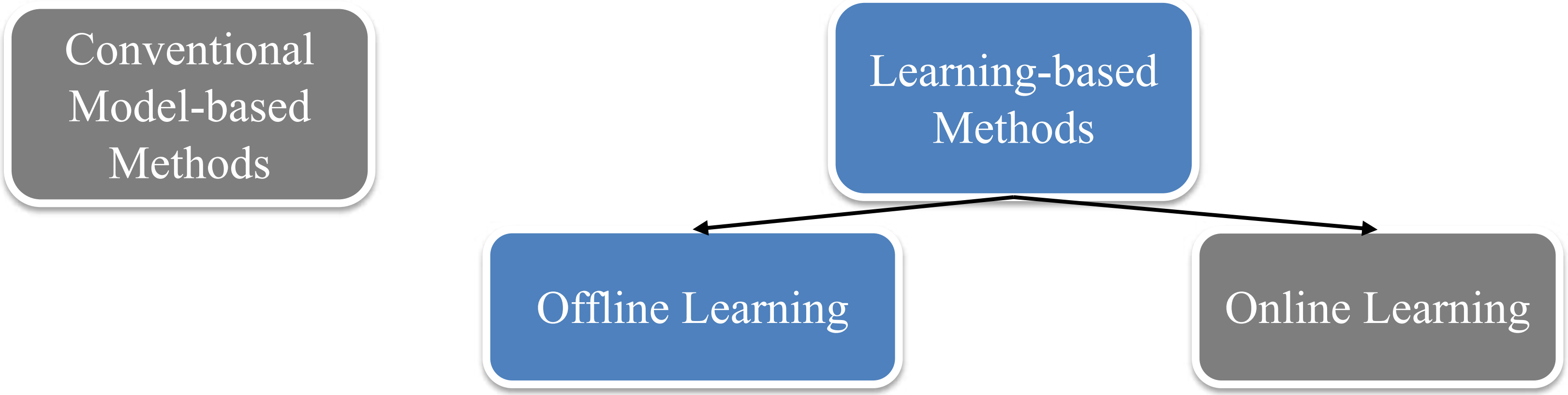
Conventional Model-based Methods

Learning-based Methods

  - Explicit system modeling
  - Channel state information (CSI) estimation

Existing Work for OTFS Symbol Detection

- Existing work for symbol detection in the OTFS system



- Offline training
  - Large amount of offline training data
  - Long training time
- Online deployment
- Issue
  - Uncertainty in generalization

Generalization Issue of Offline Learning

- Uncertainty of generalization – dynamic setups in NextG [1]
  - Mismatches between offline training and online deployment

System configuration mismatch	Scenario mismatch	Operation adaptations mismatch
E.g., subcarrier spacing, antenna configurations	E.g., outdoor vs indoor, urban vs rural	E.g., link/rank adaptation, scheduling

  - Hard to ensure robust generalization across all the cases
  - Heterogeneous nature in timescales:
    - Operation adaptations occur on a 5G slot basis (sub-millisecond)

[1] J. Xu, S. Jere, Y. Song, Y. Kao, L. Zheng, and L. Liu. "Learning at the Speed of Wireless: Online Real-Time Learning for AI-Enabled MIMO in NextG.", IEEE Communication Magazine, 2024.

Existing Work for OTFS Symbol Detection

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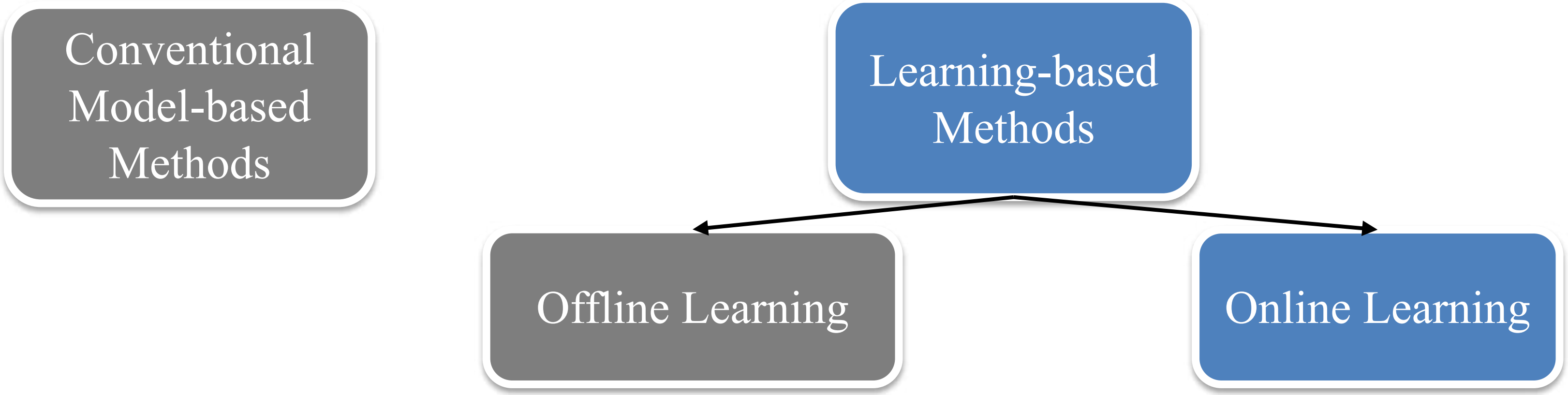

- Online training
  - Train with only over-the-air (OTA) training pilots within the 5G slot
- Online testing
  - Test within the same 5G slot

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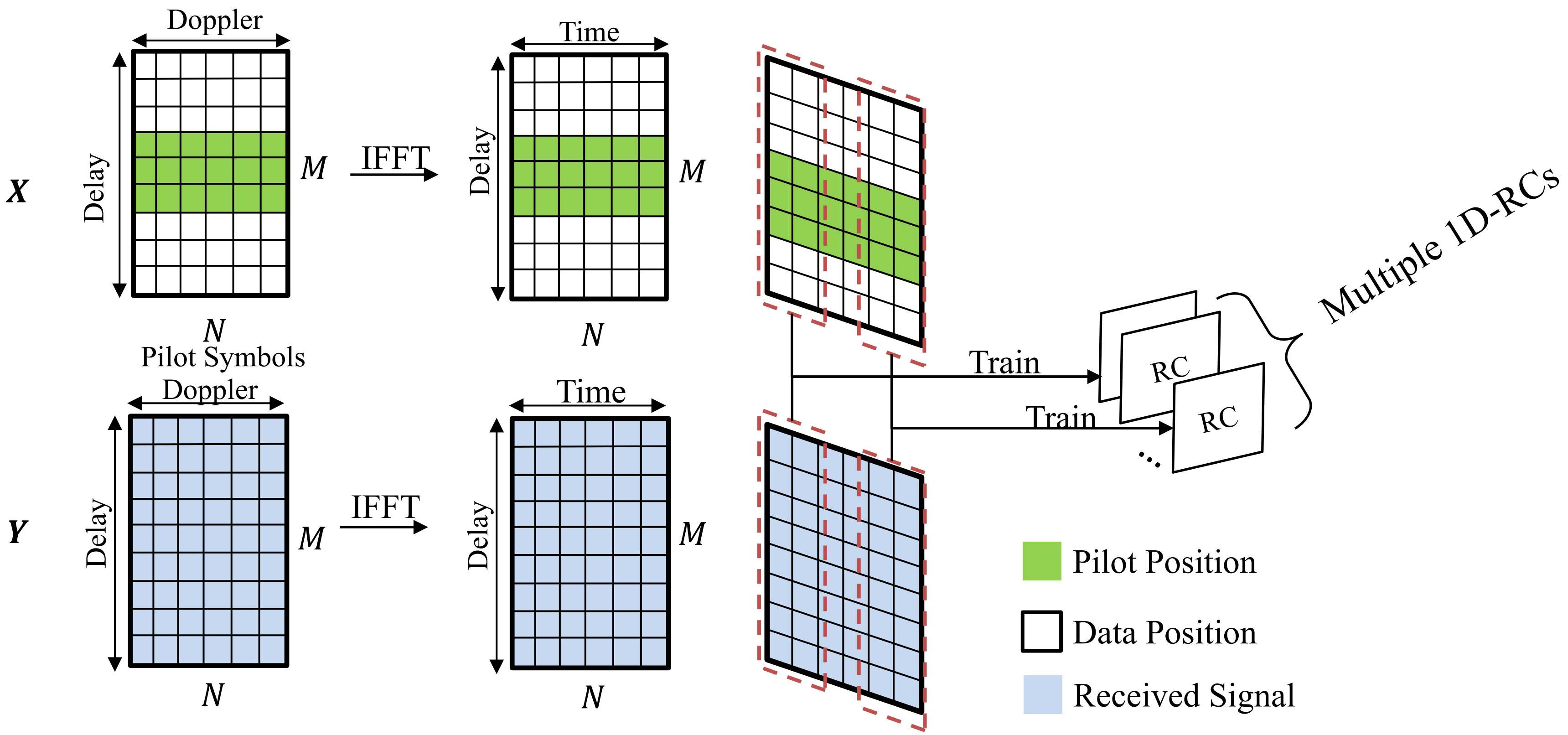
Deep Dive on Existing Online Learning Approach

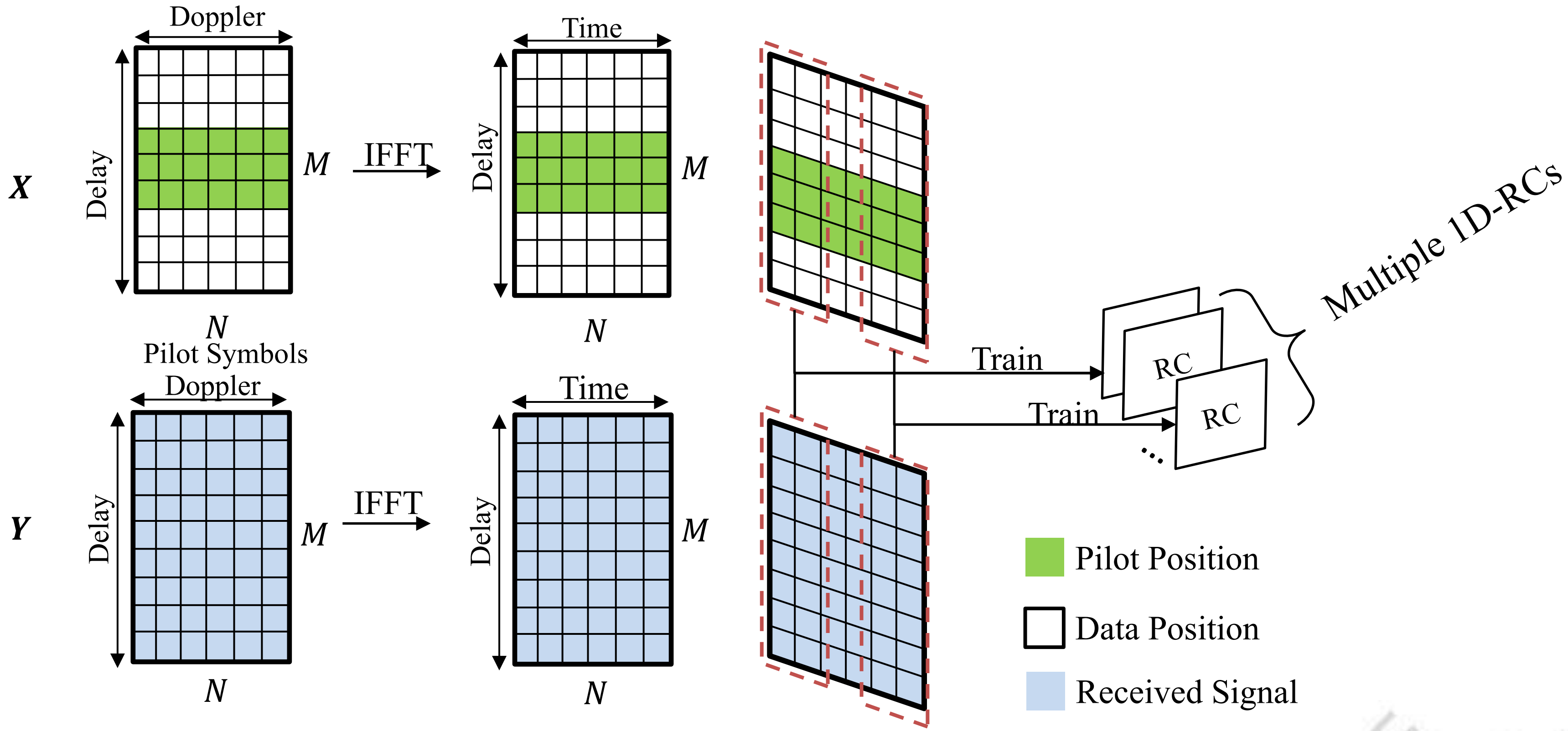
- One-dimensional reservoir computing (1D-RC) approach [2]



[2] Z. Zhou, L. Liu, J. Xu and R. Calderbank, "Learning to Equalize OTFS," in IEEE Transactions on Wireless Communications, vol. 21, no. 9, pp. 7723-7736, Sept. 2022.

Limitation of Existing Online Learning Approach

- Limitation of 1D-RC
  - Complicated parameter configuration of multiple 1D-RCs
  - Does not take advantage of the delay-Doppler channel representation



[2] Z. Zhou, L. Liu, J. Xu and R. Calderbank, "Learning to Equalize OTFS," in IEEE Transactions on Wireless Communications, vol. 21, no. 9, pp. 7723-7736, Sept. 2022.

Introduced Two-dimensional Reservoir Computing (2D-RC)

- Two-dimensional reservoir computing (2D-RC) for OTFS symbol detection
  - Addressing the limitation
    - Operate in the delay-Doppler domain with only a single neural network
    - Incorporate the delay-Doppler 2D channel interaction into the design
  - Online learning properties of 2D-RC
    - Learned with the limited OTA training pilots within the 5G slot
    - Dynamically updated on a 5G slot basis

Main Idea of 2D-RC Design

- Input-Output Relationship in the OTFS system with **rectangular** pulse shaping

$$Y[l,k] = \sum_{l'=0}^{M-1} \sum_{k'=0}^{N-1} H_{l,k}[l',k'] \, X[[l-l']_M, [k-k']_N] + N[l,k]$$

  - $Y[l,k]$: (l,k)-th element of $Y \in \mathbb{C}^{M\times N}$
  - $X[l,k]$: (l,k)-th element of $X \in \mathbb{C}^{M\times N}$
  - $H_{l,k}[l',k']$: delay-Doppler domain effective channel (2D twisted circular convolution)
- Main Idea:
  - Delay-Doppler domain effective channel works as a 2D twisted circular convolution
  - Reservoir computing (RC) performs 1D deconvolution[3]
  - Extend RC to have a new 2D structure to perform 2D circular deconvolution

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[3] S. Jere, K. Said, L. Zheng and L. Liu, "Towards Explainable Machine Learning: The Effectiveness of Reservoir Computing in Wireless Receive Processing," *MILCOM 2023 - 2023 IEEE Military Communications Conference (MILCOM)*, Boston, MA, USA, 2023, pp. 667-672.

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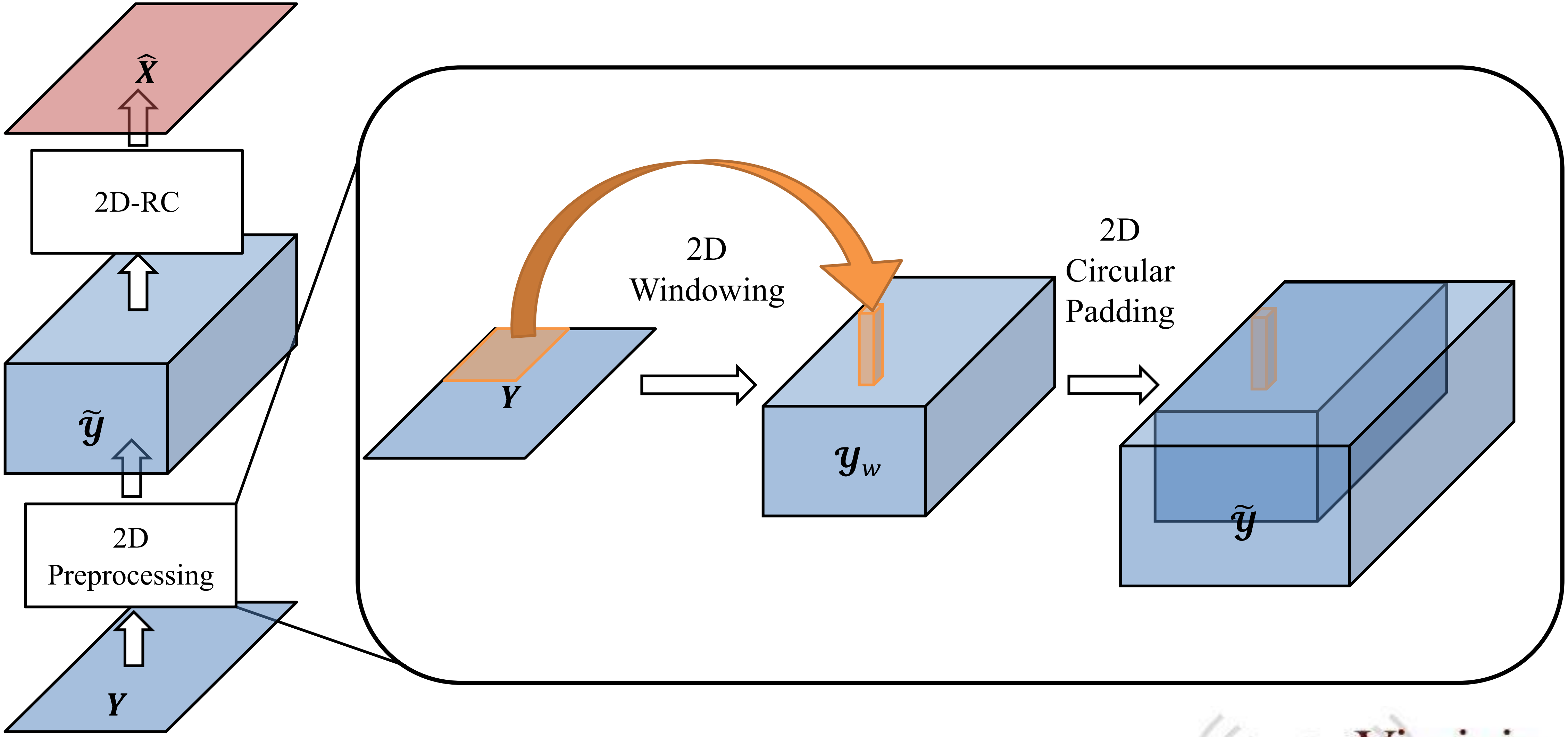
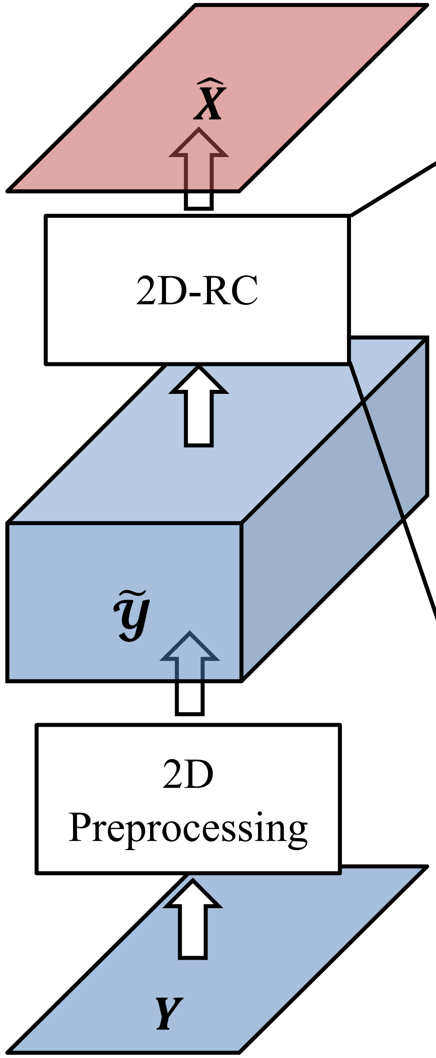
Design of 2D-RC: 2D Circular Padding



Design of 2D-RC: 2D Processing



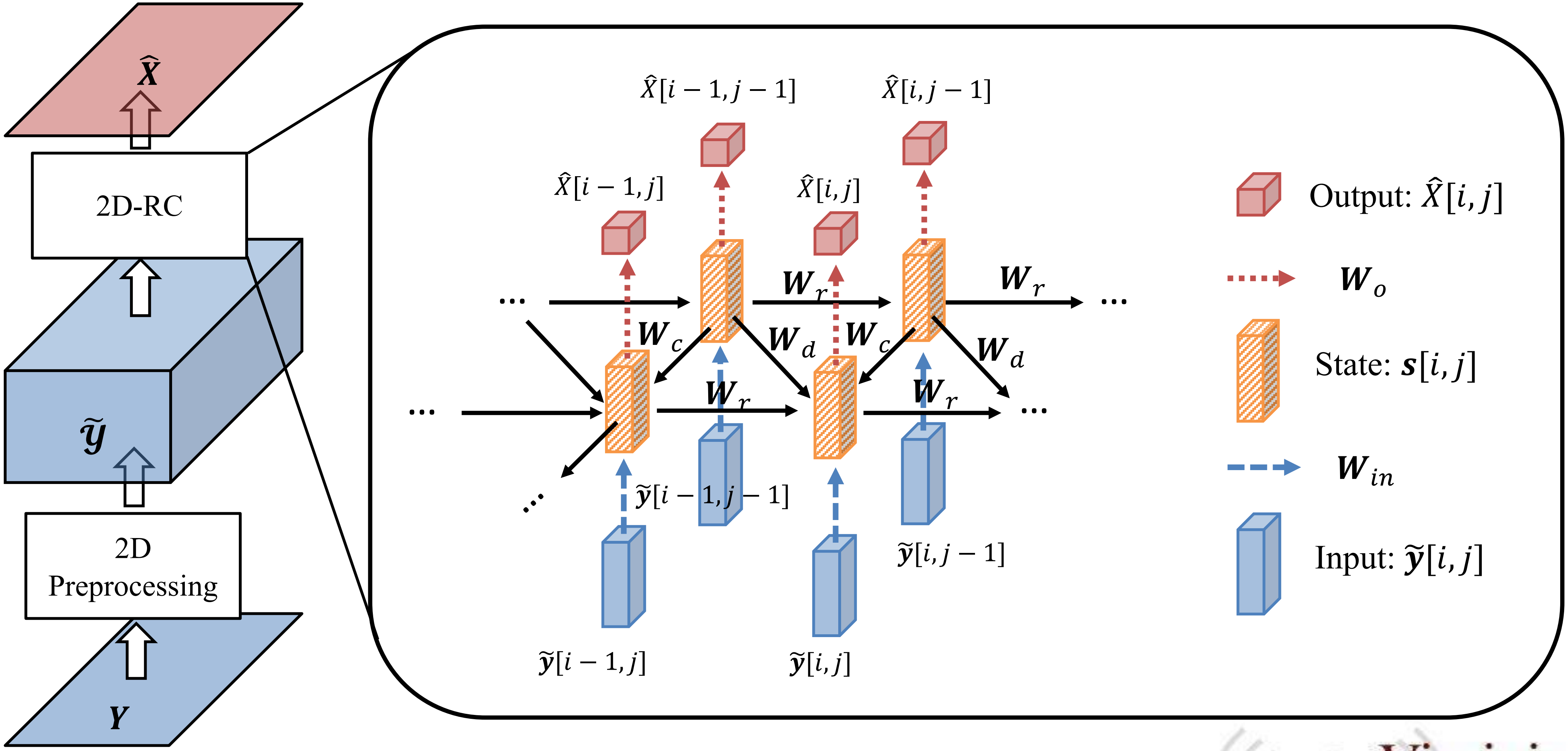
- The state transition equation and output estimation equation of 2D-RC

$$\boldsymbol{s}[i,j] = f(\boldsymbol{W}_r\boldsymbol{s}[i-1,j] + \boldsymbol{W}_c\boldsymbol{s}[i,j-1] + \boldsymbol{W}_d\boldsymbol{s}[i-1,j-1] + \boldsymbol{W}_{in}\widetilde{\boldsymbol{y}}[i,j])$$

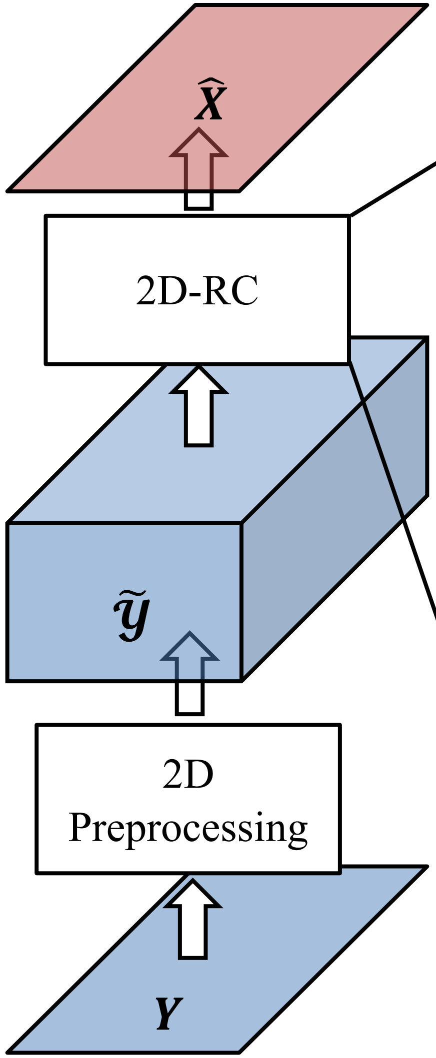
$$\widetilde{\boldsymbol{s}}[i,j] = \begin{bmatrix} \widetilde{\boldsymbol{y}}[i,j] \\ \boldsymbol{s}[i,j] \end{bmatrix}$$

$$\widehat{\boldsymbol{X}}[i,j] = \boldsymbol{W}_{out}\widetilde{\boldsymbol{s}}[i,j]$$

Design of 2D-RC: 2D Processing



Properties and Advantages of 2D-RC



- Properties of 2D-RC
  - Fixed and randomly initialized input weights and reservoir weights

$$\boldsymbol{W}_{in}, \boldsymbol{W}_{r}, \boldsymbol{W}_{c}, \boldsymbol{W}_{d}$$

  - Trainable weights:

$$\boldsymbol{W}_{out}$$

- Advantages:
  - Simple and light training procedure
  - Learn with a very limited amount of training data and short training time
  - Suitable for online learning on a 5G slot basis

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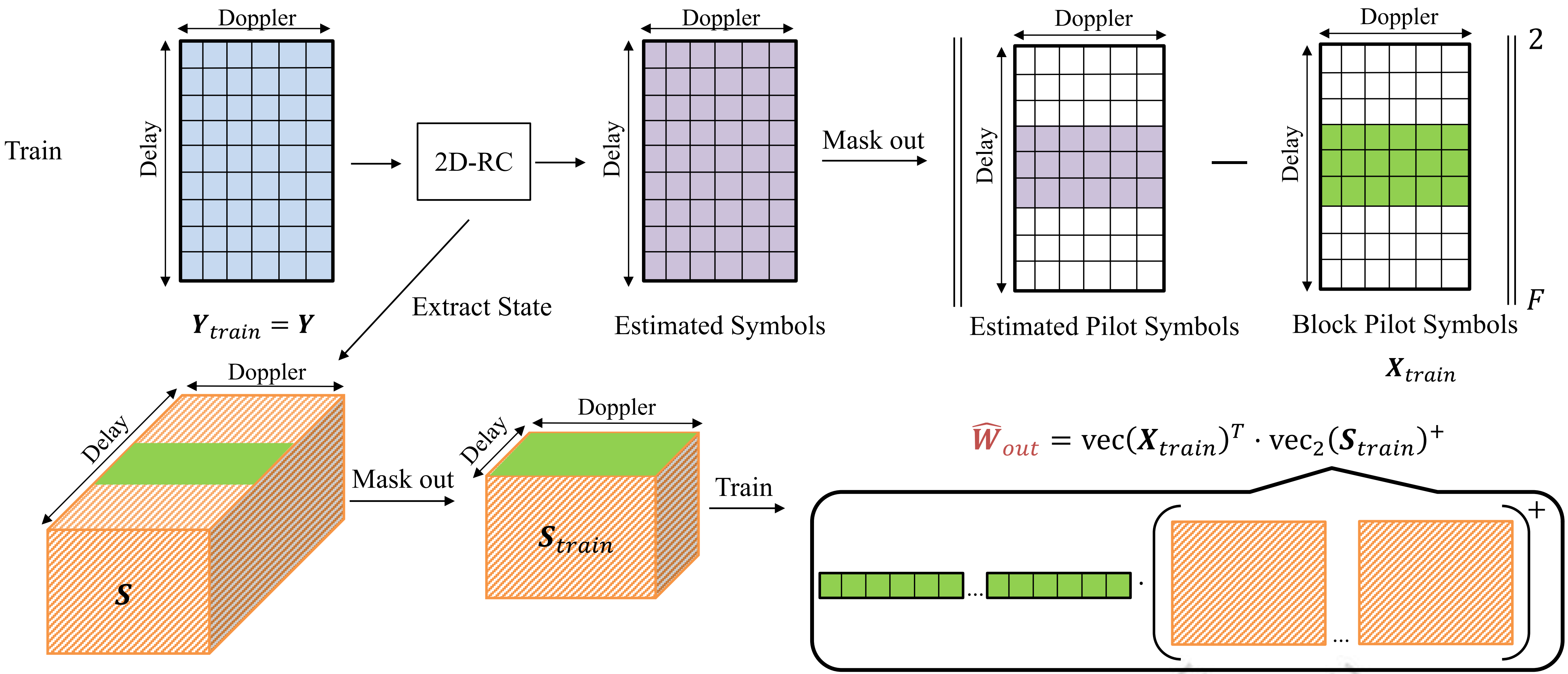
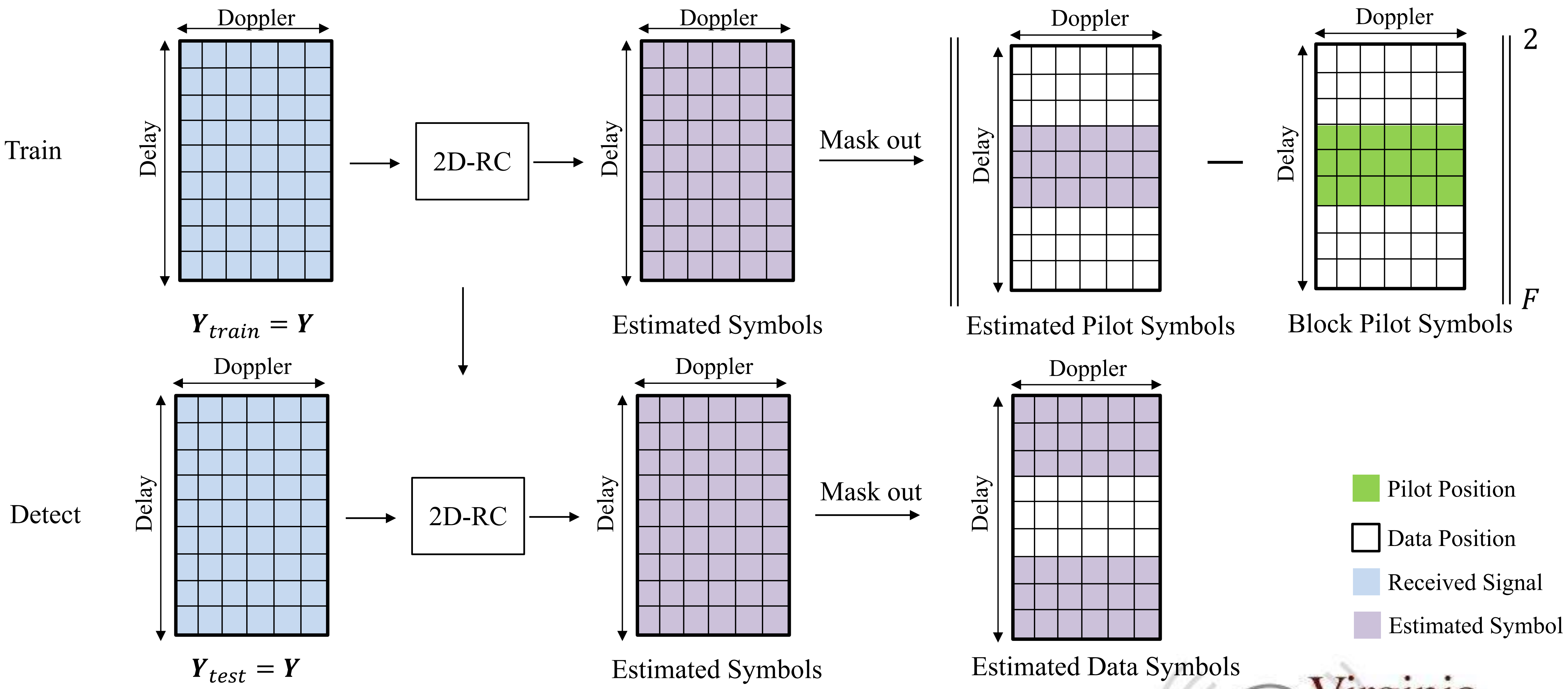
Training 2D-RC

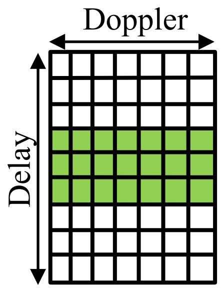


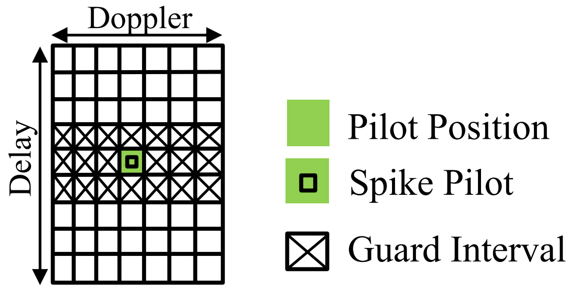
Detecting with 2D-RC



Performance Comparison

- 3GPP 5G NR clustered delay line (CDL) channel
  - User speed: 150 km/h
  - Delay profile: CDL-C
  - Carrier frequency: 4 GHz
  - Subcarrier spacing: 15 kHz
  - Number of Doppler bins (symbols): 14
  - Number of delay bins (subcarriers): 1024

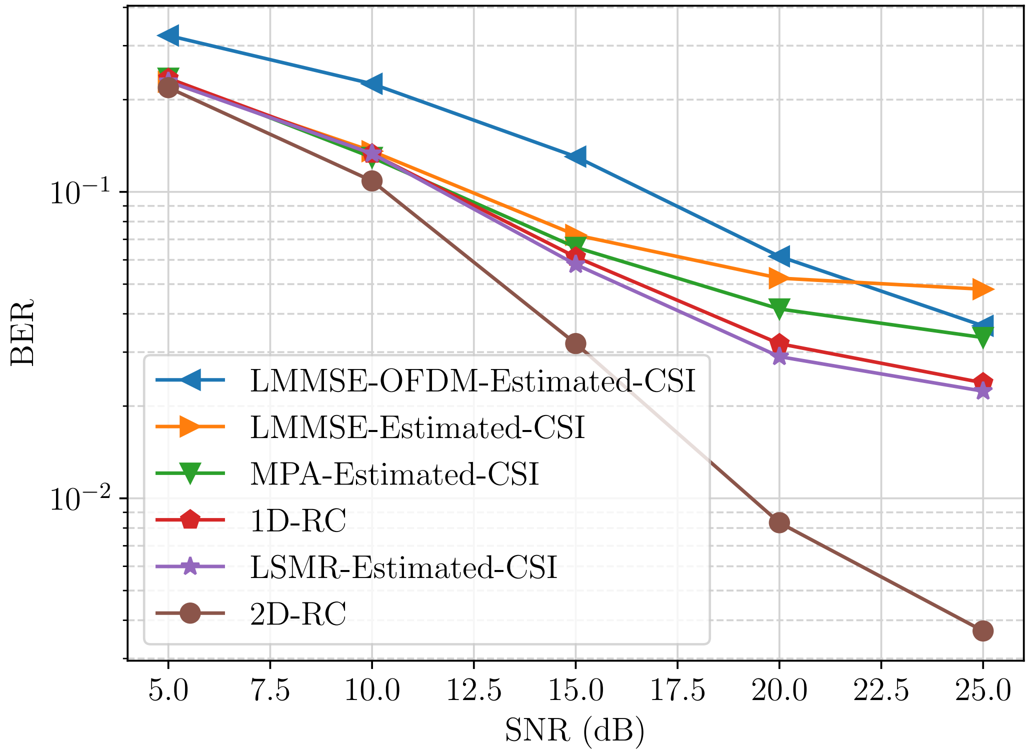




Learning-based approaches:
- Block pilot pattern

Model-based approaches:
- Spike pilot pattern

Training overhead: 4.7%



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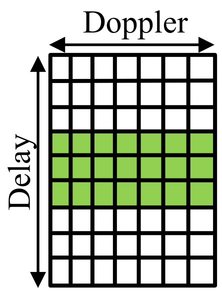

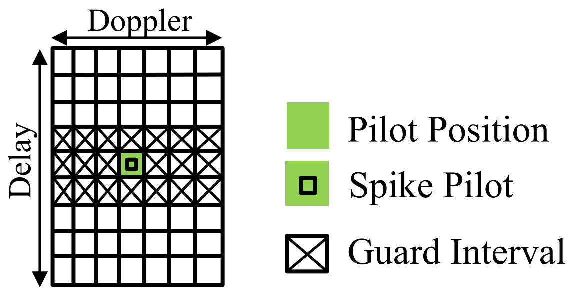

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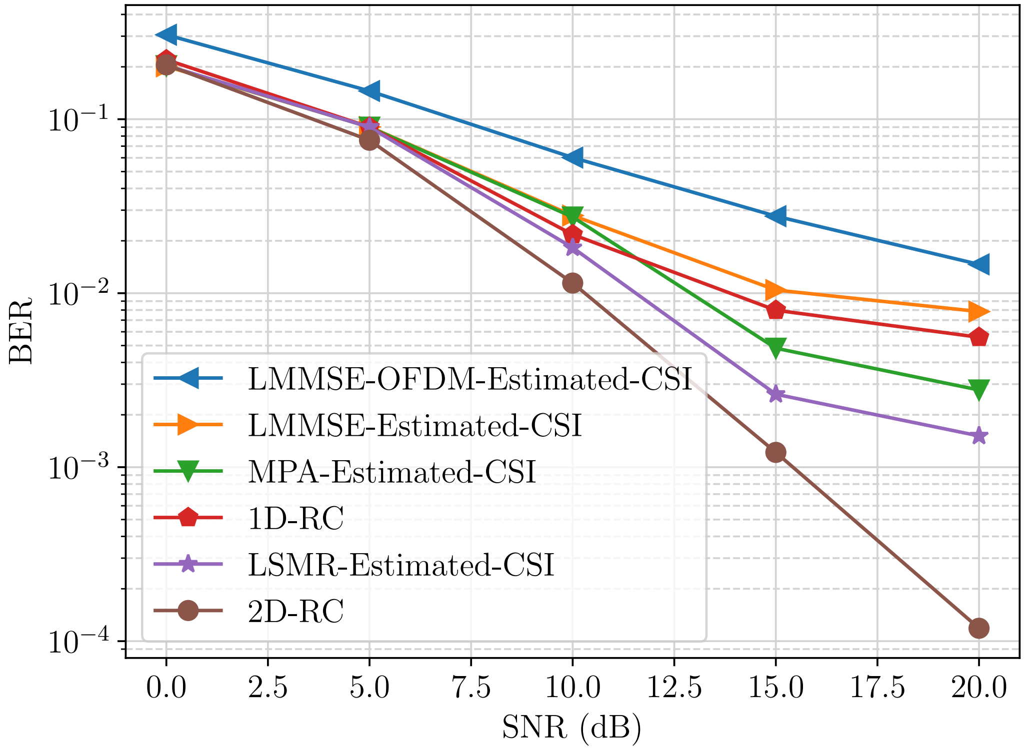

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Summary

- Introduced 2D-RC approach for OTFS symbol detection
  - Learned with the limited OTA training pilots within the 5G slot
  - Dynamically updated on a 5G slot basis

  - Achieve these online properties by
    - Incorporating the delay-Doppler domain 2D channel interaction into the design
    - Extending RC to have a new 2D structure to perform 2D circular deconvolution

Thank You!

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