Computation Offloading Scheduling for Deep Neural Network Inference in Mobile Computing

Yubin Duan and Jie Wu
Dept. of Computer and Information Sciences
Temple University, USA

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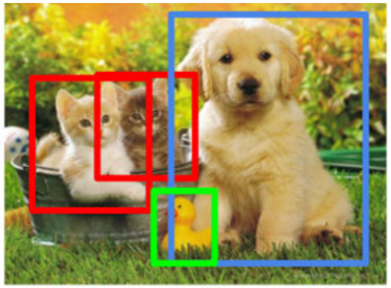
Outline

1. Introduction
2. Model
3. Tree-structure DNN Scheduling
   - Path-wise scheduling
   - Layer-wise scheduling
4. Scheduling for DAG-Style DNNs
5. Experiment
6. Conclusions

1. Introduction

- DNN inference in mobile applications
  - Image classification
  - Object detection

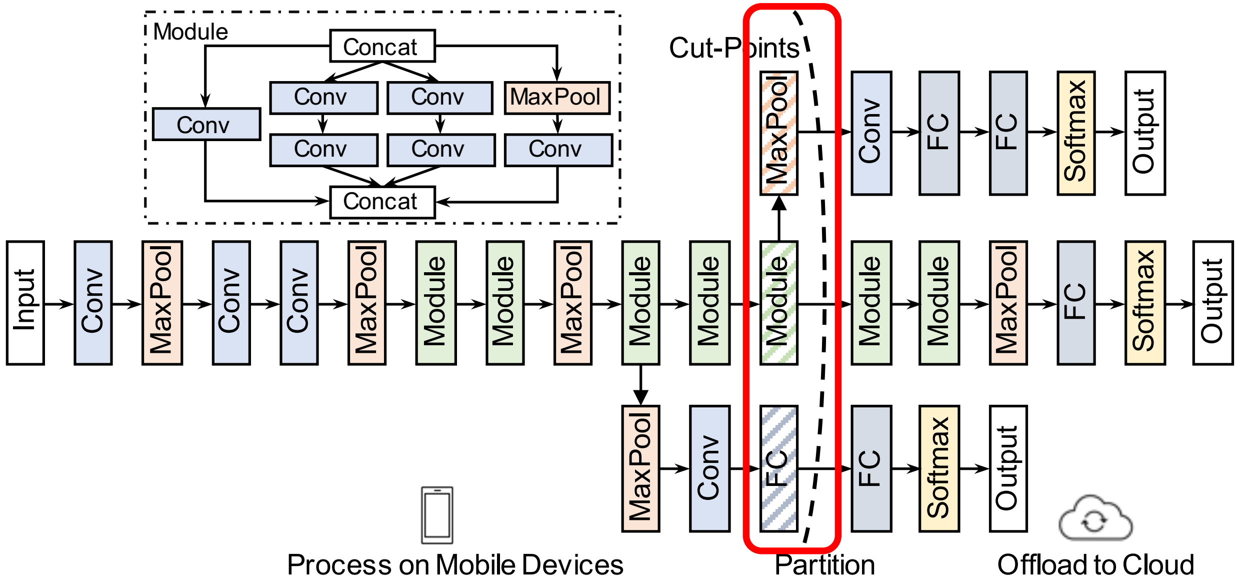


CAT, DOG, DUCK

- QoS measurement
  - Inference latency
- Cooperative DNN inference
  - Computation offloading

Motivation

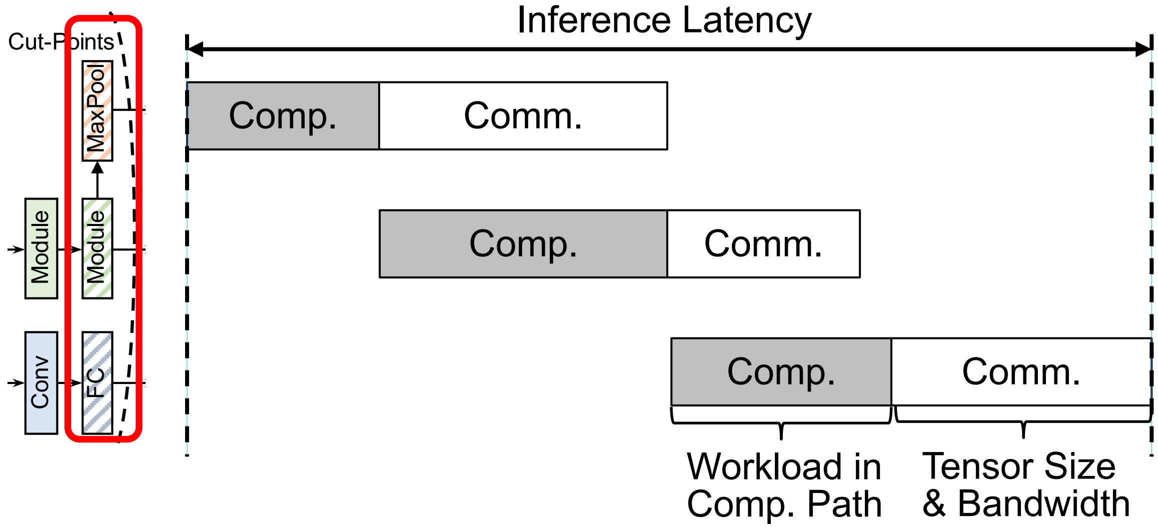
- Offloading pipeline
  - May have multiple offloading subtasks



- Scheduling problem
  - Computation and communication priorities

2. Model

- Two-stage offloading pipeline



  - Comp.: process DNN layers from input to cut-points
  - Comm.: upload intermediate results to cloud servers
  - Cloud processing time is negligible

Problem Formulation

- Objective
  - Minimize inference latency for a given DNN

$$\min_{\sigma} \quad \tau = t_{|S|} - t_0$$

  - Recursive calculation of the completion time

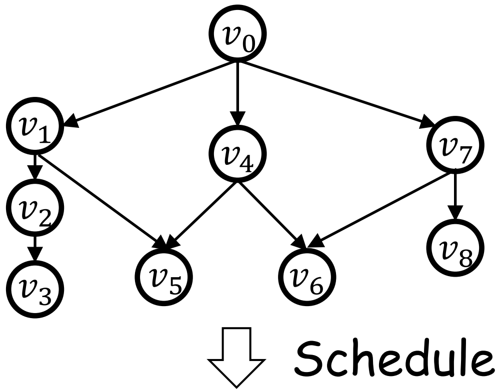
$$t_i = \max\{t_0 + \sum_{k=1}^{i} f(x_i), t_{i-1}\} + g(x_i), \forall x_i \in \sigma$$

- Constraints
  - Precedence constraint

$$i \leq j, \forall x_i \prec x_j, \forall x_j \in \sigma$$

  - Permutation constraint

$$\cup_{x_i \in \sigma} x_i = S, |\sigma| = |S|$$

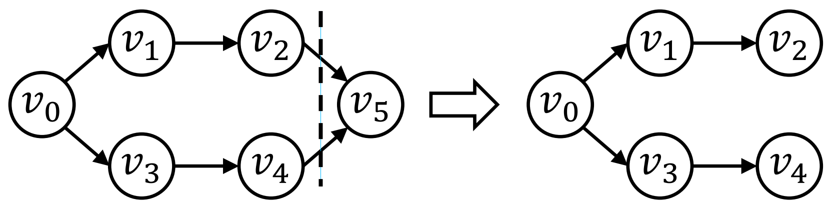


$\sigma = [x_0, x_1, \ldots, x_8]$

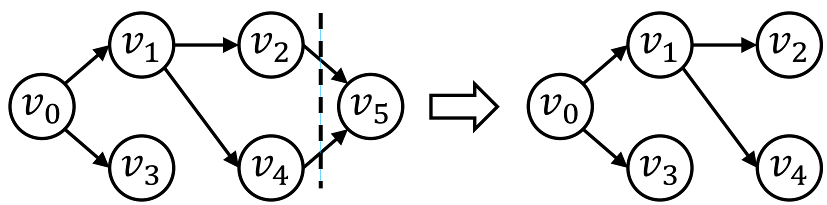
A permutation of $\{v_0, \ldots, v_8\}$

DNN Structures after Partition

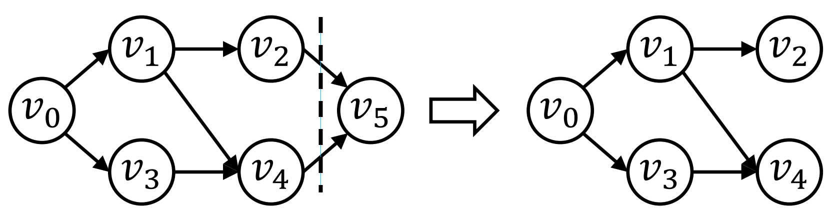
- Tree-structure
  - Multi-path tree



  - General tree

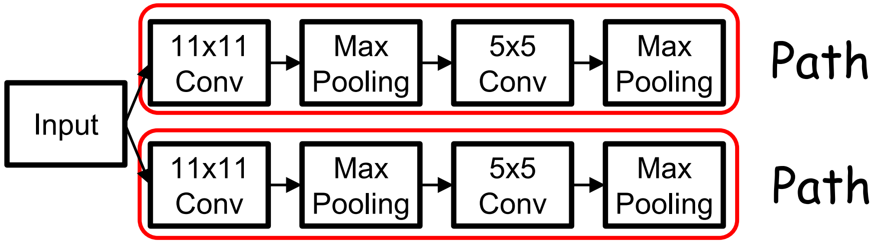


- DAG

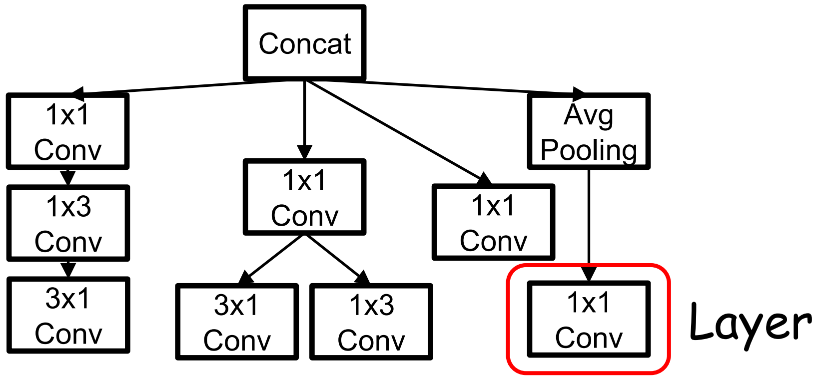


3. Tree-structure DNN Scheduling

- Scheduling granularities
  - Path-wise scheduling
    - Can be optimally solve by applying Johnson's rule

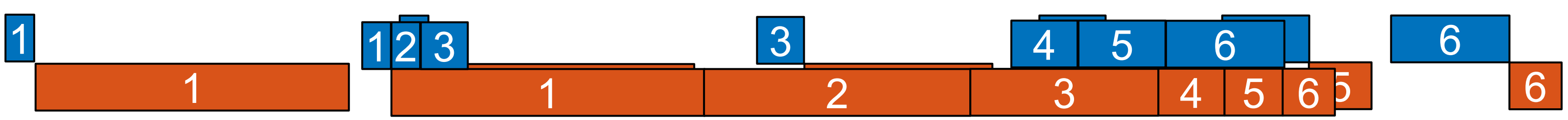


  - Layer-wise scheduling
    - Extend Johnson's rule for the optimal solution



Path-wise Scheduling

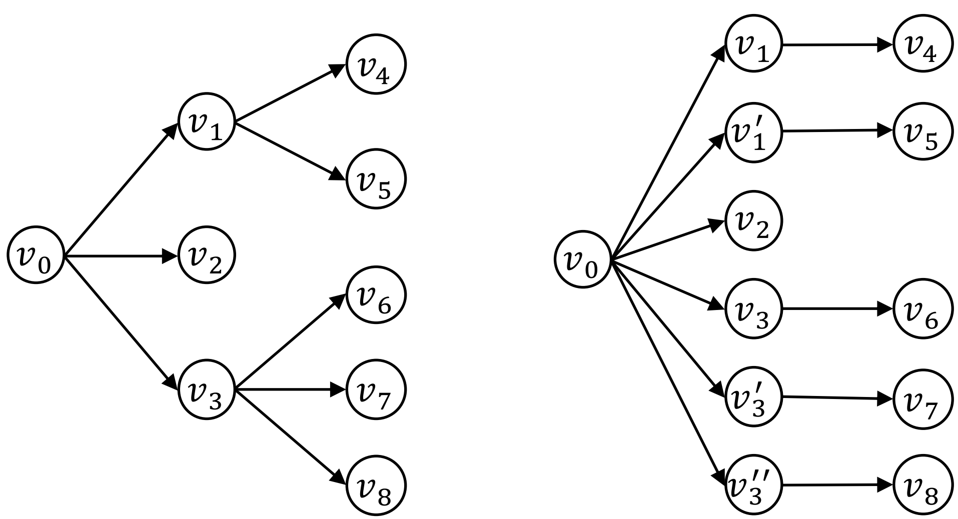
- Optimal scheduling with Johnson's rule
  - Each path is a task with two operations
  - Split tasks into comm./comp.-domination groups
  - H = {1, 2, 3}, increasing order of comp.
  - L = {4, 5, 6}, decreasing order of comm.



- Can extend to any structures with conversion

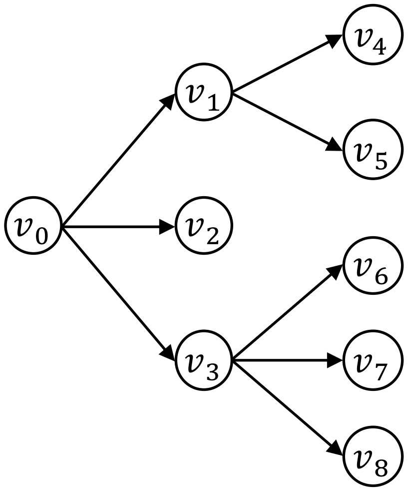
DAG Conversion

- Apply path-wise scheduling on arbitrary DNNs
  - Breadth-first search on graph
  - Duplicate each internal nodes
  - Avoid re-processing duplicated layers in inference



Layer-wise Scheduling

- For arbitrary tree-structure DNNs
  - Johnson's rule + conversion is suboptimal
  - Challenge: precedence constraints
- Recursively merge schedules of subtrees
  - Schedule of a subtree:
    - list covering all its node
  - At internal nodes:
    - Merge lists of children nodes
    - Group it with head of the merged list
  - Johnson's rule for comparisons



Layer-wise Scheduling

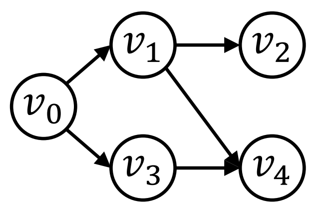
- Property

> Theorem 1: The schedule generated by the recursive merging approach is optimal for tree-structure DAGs.

- Proof
  - Sketch : mathematical induction
    - Merging and grouping will not lose optimal schedule
  - Insights:
    - Merging preserve the precedence constraints
    - For nodes without precedence constraints, Johnson's rule finds their optimal schedule

4. Scheduling for DAG-Style DNNs

- More complex precedence constraints
  - DAG scheduling is NP-hard
  - Inspired by topological sort
    - Iteratively sort nodes with no successors with Johnson's rule
    - Scheduled nodes are removed from the DAG



Schedule

$$\sigma = [v_0, v_1, v_3, v_4, v_2]$$

5. Experiment

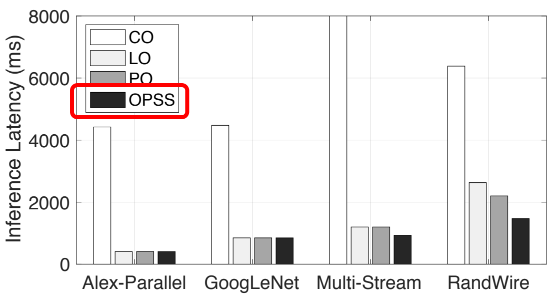
- Prototype implemented with PyTorch
  - gRPC is used for offloading
  - PyTorch Profiler is used to measure comp. time
- DNNs used in evaluation
  - Alex-Parallel[1]: multi-path tree
  - GoogleNet[2]: tree
  - Multi-Stream Network[3]: tree
  - RandWire[4]: DAG

[1].K. He et. al., "Deep residual learning for image recognition," in IEEE CVPR, 2016, pp. 770–778
[2].C. Szegedy et. al., "Going deeper with convolutions," in IEEE CVPR, 2015, pp. 1-9.
[3].Y.-W. Chao, et. al., "Learning to detect human-object interactions," in IEEE WACV, 2018, pp. 381-389.
[4].S. Xie, et. al., "Exploring randomly wired neural networks for image recognition," in IEEE ICCV, 2019, pp. 1284–1293.

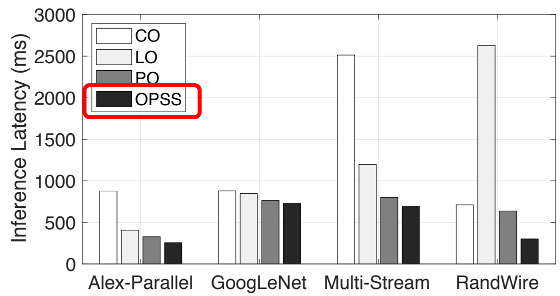
Experiment Results

- Latency on different network environment

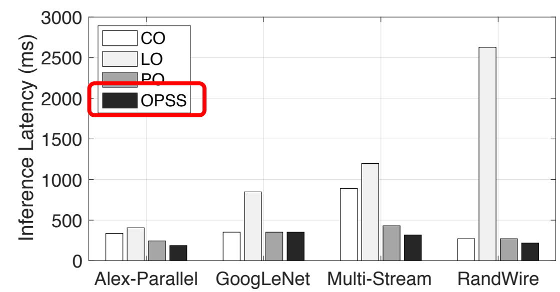
  (CO: Cloud-Only, LO: Local-Only, PO: Partition-Only)



3G

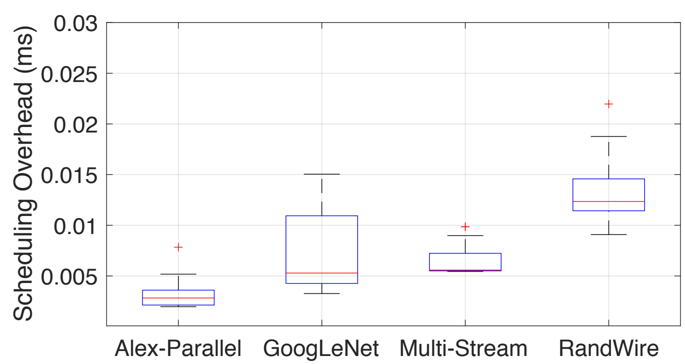


4G



Wi-Fi

- Scheduling overhead



6. Conclusion

- Proposed an offloading pipeline
  - Hide comm. time behind comp.
- Optimal path-wise scheduling
  - Intend for trees with multi-paths
  - Can apply to arbitrary DNNs with conversion
- Optimal layer-wise scheduling
  - Can apply to arbitrary tree-structure DNNs
  - Recursively merge schedule lists
- Evaluation on a prototype system

Questions

yubin.duan@temple.edu