Computation Offloading Scheduling for Deep Neural Network Inference in Mobile Computing

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Outline

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1. Introduction

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

- **QoS measurement**
  - Inference latency

- **Cooperative DNN inference**
  - Computation offloading
**Motivation**

*Offloading pipeline*
- **May have multiple offloading subtasks**

*Cut-Points*

**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
    \[
    \min_{\sigma} \tau = t_{|S|} - t_0
    \]
  - 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
    \[
    i \leq j, \forall x_i < x_j, \forall x_j \in \sigma
    \]
  - Permutation constraint
    \[
    \bigcup_{x_i \in \sigma} x_i = S, |\sigma| = |S|
    \]
    \[
    \]
    A permutation of \(\{v_0, \ldots, v_8\}\)

![Diagram](image.png)
DNN Structures after Partition

- **Tree-structure**
  - Multi-path tree
    - ![Multi-path tree diagram]
  - General tree
    - ![General tree diagram]

- **DAG**
  - ![DAG diagram]
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

![Diagram of DAG conversion](image)
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

\[ \begin{array}{c}
\text{v}_0 \\
\downarrow \\
\text{v}_1 \\
\downarrow \\
\text{v}_2 \\
\downarrow \\
\text{v}_3 \\
\downarrow \\
\text{v}_4 \\
\downarrow \\
\text{v}_5 \\
\downarrow \\
\text{v}_6 \\
\downarrow \\
\text{v}_7 \\
\downarrow \\
\text{v}_8 \\
\end{array} \]
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

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

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Experiment Results

- Latency on different network environment
  (CO: Cloud-Only, LO: Local-Only, PO: Partition-Only)

- 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

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