Application Provisioning in Fog Computing-enabled Internet-of-Things: A Network Perspective

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Outlines

Background and Motivation

System Modeling

Algorithm Design and Analysis

Performance Evaluation

Discussions, Future Work and Conclusions

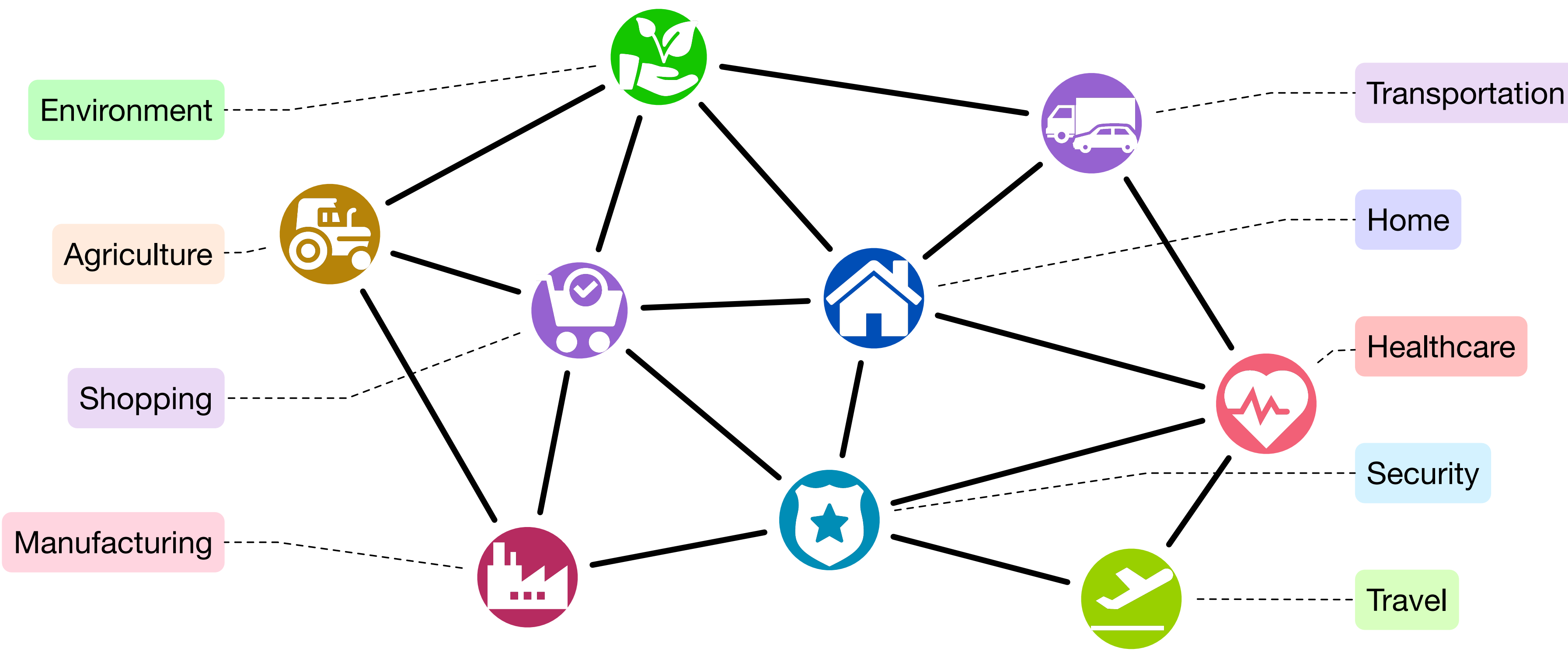
the IoT

All things are connected through ~~**the Force**~~.

— *The Jedi Faith*

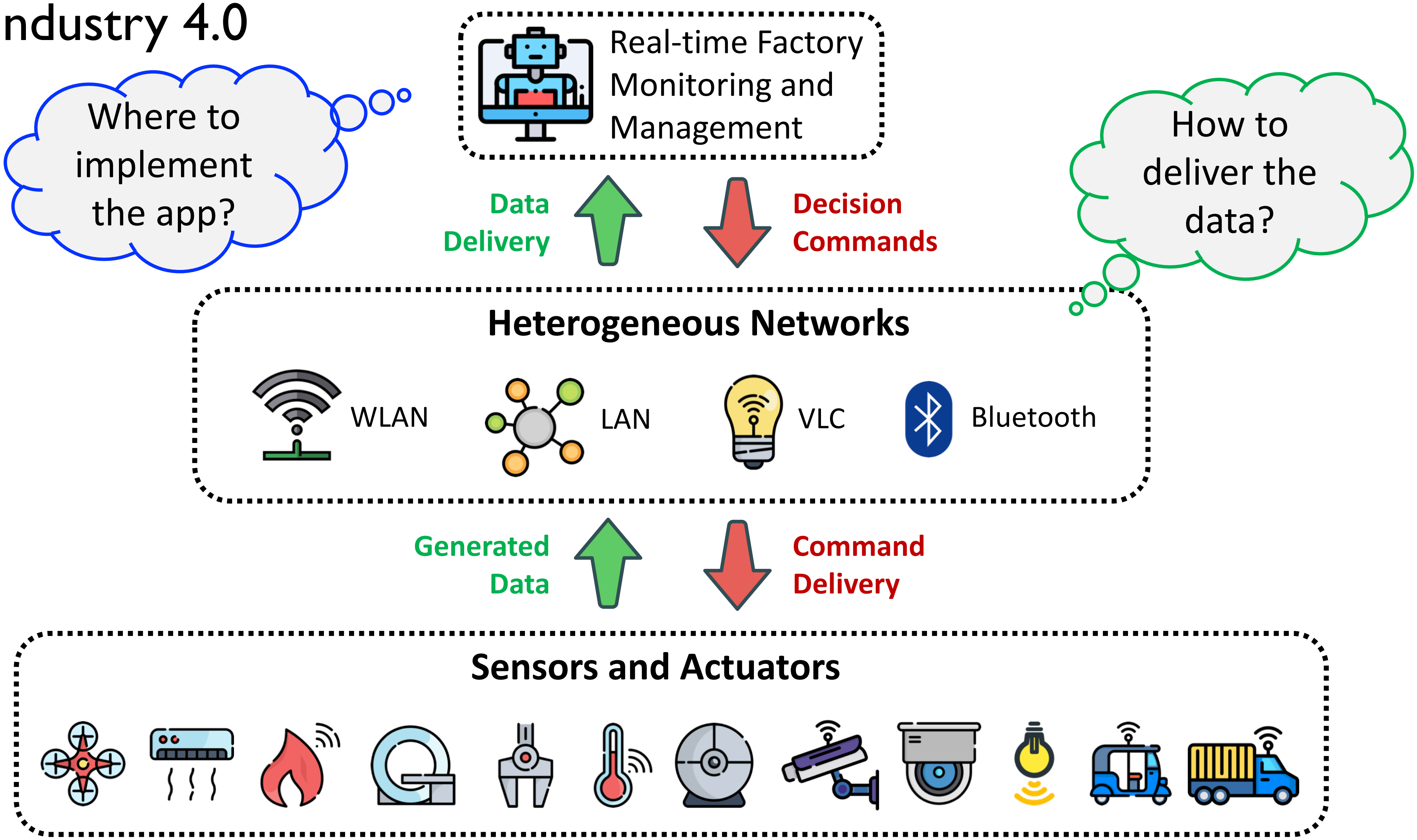
IoT: The Future Internet

- IoT is the future Internet that connects every aspect of our work and life.



A Typical Scenario in IoT

- Industry 4.0



Current Approaches

Application Hosting

Local Server:
- High CAPEX/OPEX
- Non-elastic

Cloud Computing:
- WAN congestion
- Long latency
- Unpredictable

Mobile Offloading
- one-hop
- network-agnostic

Data Delivery

ICN:
- On-demand
- QoS-agnostic
- Not real-time

TE:
- BW-oriented
- Delay-agnostic

QoS Routing:
- Single-path
- No sharing

Traditional view: **No coordination between two domains!**

Our Approach: Overview

Problem Modeling

1) Joint application hosting and data routing.
2) General graph-based IoT network model.
3) Application QoS requirements.
4) Two types of applications.
5) Inter-application resource sharing.

Algorithmic Results

1) Four variants of the problem proved NP-hard.
2) FPTASs for three variants.
3) Randomized approximation for the forth one.

Next Steps (Future Work)

1) Computation-aware provisioning.
2) Reliability and security.
3) IoT and fog economics and mechanism design.

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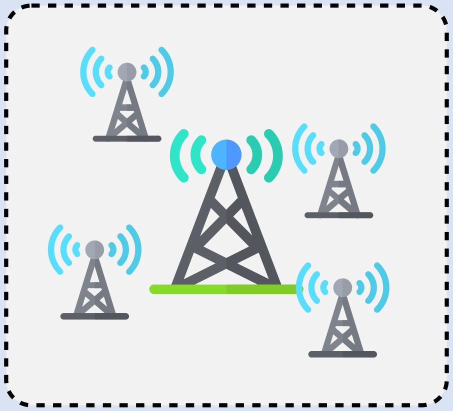
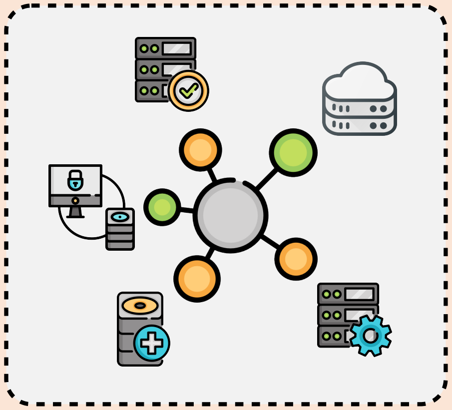
IoT Network: A General Model

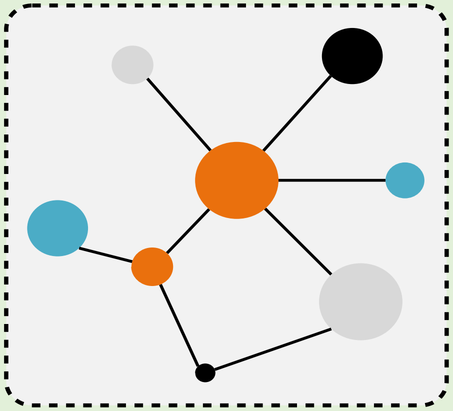
- Challenge: heterogeneous network environments



Wireless RANs:
- Geo-distributed
- Limited capacity
- Interference



Edge Network:
- Complex topo
- Distributed
- Dynamic load

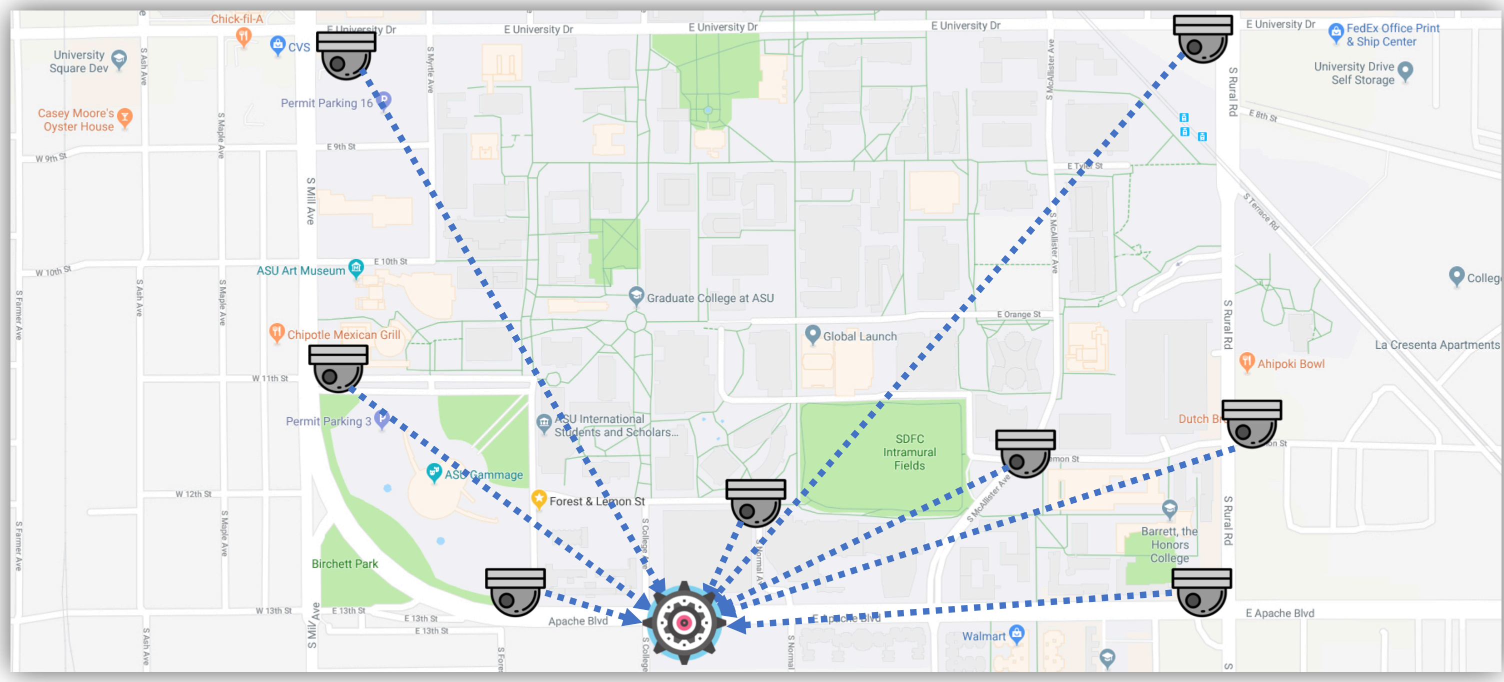


Backbones:
- Large-scale
- High latency
- ISP policies

- Model: general weighted directed graph, with some fog nodes
  - Weights: capacity & delay

Real-time IoT Applications

- Application = Logic + Data
  - Logic: data processing unit
  - Data: from multiple sources in the network



  - ***Requirements:***
    1) Bandwidth: channels supporting each data source's transmission demand
    2) Real-time: channel latency up to a required bound

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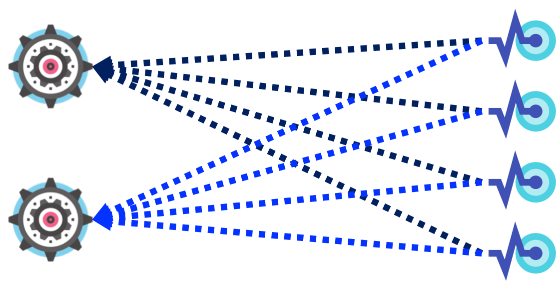
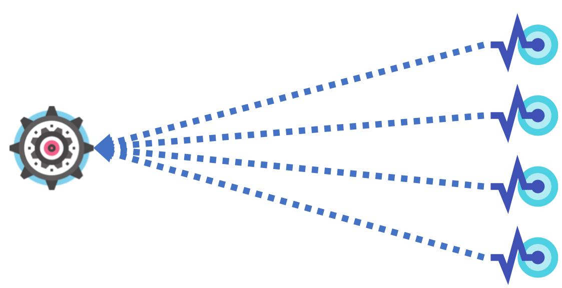
Two Types of Applications

- Parallelizable Applications (P)
  - Logic splittable among multiple parallel instances
  - ***Requirement:*** data in the same time interval received at the same instance
  - Example: stateless sensor data fusion



- Non-Parallelizable Applications
  - Logic has to be centrally implemented



Some icons are taken from icons8.

Two Provisioning Scenarios

- Single Application Provisioning (SAP)
  - Provisions one application at a time
  - Low complexity, suitable for general online provisioning
  - No inter-application resource sharing

- Multi-Application Provisioning (MAP)
  - Jointly provisions multiple applications simultaneously
  - Better optimization across applications, more balanced load
  - High complexity, weaker performance guarantee

Problem Statement: Overview

- **Inputs:**
  - Network topology
  - One application / Multiple applications

- **Outputs:**
  - Host designation for each application
  - Data routing for each application's each data source
    - Multi-path routing for best optimization

- **Constraints:**
  - Bandwidth demand of each application's each data source
  - Capacity limit of each link
  - Latency constraint of each application

- **Objective:**
  - Maximize **Inverse** Maximum Link Load (Load Balancing)

The Provisioning Problems are Hard!

- Four variants of the problem:

  (O- stands for the optimization version with load balancing objective)

  - **PO-SAP**: Single Application Provisioning for Parallelizable Applications
  - **O-SAP**: Single Application Provisioning for Non-Parallelizable Applications
  - **PO-MAP**: Multi-Application Provisioning for Parallelizable Applications
  - **O-MAP**: Multi-Application Provisioning for Non-Parallelizable Applications

Lemma: All four variants are NP-hard!

Proof: A simple reduction from the *MultiPath routing with Bandwidth and Delay constraints (MPBD)* problem, which is NP-hard.

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Our Results

- **Fully Polynomial-Time Approximation Scheme (FPTAS)** can achieve the best trade-off between time and accuracy
  - Approximation ratio: $(1-\epsilon)$ – For maximization problem
  - Time complexity: $O(\text{poly}(1/\epsilon) \times \text{poly}(\text{input}))$
  - In practice, one can arbitrarily tune ϵ to get best accuracy within time limit.

- Our results:

Theorem:

1) Three variants (**PO-SAP, O-SAP, PO-MAP**) admit FPTASs.
2) For **O-MAP**, there is a non-trivial approximation algorithm.

A Brief Overview of Our FPTASs

- Idea:
  - Distribute flow as even as possible
    - Push flow along under-loaded links/paths
  - Fractionalize host designation based on flows

- Approach: Primal-Dual algorithm
  - Dual lengths: exponential in primal flow values
  - Flow pushing: along dual-shortest paths
  - Flow distribution: proportional to each flow's demand
  - Stopping criteria: total dual length exceeding balancing threshold

- Analysis:
  - Flows bounded by dual lengths achieve approximately even distribution

Randomized Algorithm for O-MAP

- Randomized Algorithm:
  1) Derive fractional approximated solution for PO-MAP;
  2) Independent random host selection for each application.

- Analysis:
  - Non-trivial approximation ratio through the Chernoff bound.

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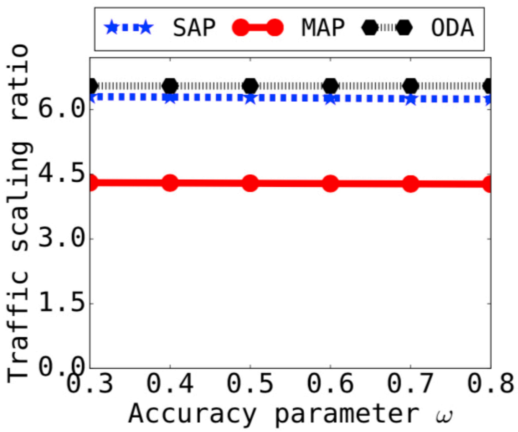
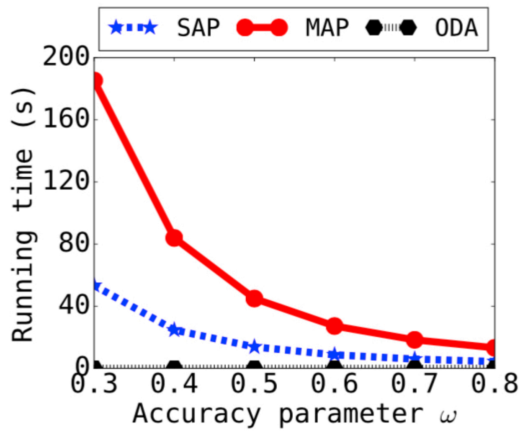
Simulation Settings

- Simulated network scenarios:
  - Random Waxman network (α=β=0.6)
    - Link capacities: [10, 100] Mbps
    - Delays: [1, 10] ms
  - 20% random fog nodes
  - 5 IoT applications
    - Data sources: [3, 10]
    - Bandwidth demands / source: [1, 25] Mbps
    - Latency bounds: [15, 25] ms
  - Approximation parameter: ϵ=0.5
- Comparisons:
  - ODA: latency-agnostic optimal solution (upper bound)
  - NS, RS: nearest / random host designation
  - GH, DA: greedy shortest-path routing / optimal delay-agnostic routing

Comparison Results



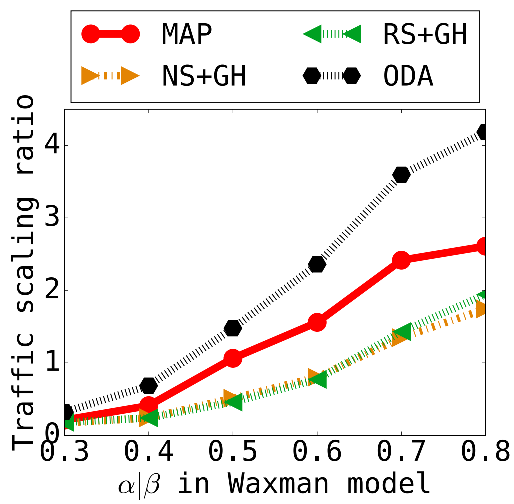
(a) Traffic scaling ratio

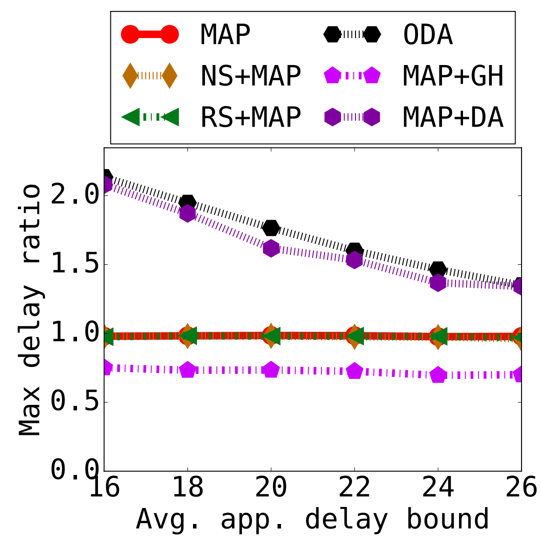


(b) Running time

With ϵ=0.5, both O-SAP and O-MAP achieves much better performance than proved bounds.

O-MAP improves upon heuristics in terms of both HD and DR, with strictly bounded delay.





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Other Perspectives and Beyond

- So far, we've talked about
  - Topology,
  - Link bandwidth and delay, and
  - Routing.

  Network Perspective

- What we haven't considered
  - Fog computing capacities,
  - Task scheduling and completion,
  - Migrations, etc.

  Computing Perspective

  - Reliability, security and privacy.

  Security Perspective

  - Incentives, pricing, and
  - Payment methods.

  Economics Perspective

- A **unified approach** is in need for fog computing-enabled IoT.

Our Conclusions

- Application Provisioning in IoT in the Network Perspective
  - General graph model for complex network environments
  - Application requirements: bandwidth and delay
  - Objective: network-wide load balancing

- Algorithmic solutions
  - FPTASs for three variants
  - Randomized approximation for the forth one

- Future directions
  - Need for unified optimization for IoT application provisioning

Thank you very much!

Q&A?

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