MicroOpt: Model-driven Slice Resource Optimization in 5G and Beyond Networks

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RESEARCH PROBLEM

BACKGROUND

- **5G Network:** Comprises Virtual Network Functions (VNFs) within the Radio Access Network (RAN), Transport, and Core
- **Network Slicing:** Involves creating isolated, virtual networks tailored to specific use-cases (e.g., eMBB slices tailored of VR/XR, URLLC slice for remote driving, telesurgery and mMTC for IOT applications)
- **Slice QoS & SLA:** Service Level Agreements (SLAs) define the minimum Quality of Service (QoS) 5G slices must receive
- **Resource Allocation vs. QoS:** The amount of resources allocated to VNFs directly impacts the slice's QoS

MOTIVATION

- **Dynamic Traffic Patterns:** Slices experience time-varying traffic
- **Resource Efficiency:** Resource allocation for peak traffic leads to resource over-provisioning

PROBLEM STATEMENT & CHALLENGES

- **Resource Optimization:** Minimize resource allocation while meeting QoS requirements
  - **Network Complexity:** Accurately modeling complex, multi-VNF slices
  - **Real-Time Adaptation:** Fast, efficient resource adjustment to varying slice traffic

SOLUTION

- **ML-Based VNF & Slice Modeling:** Leveraging machine learning for modeling VNFs that can be composed to create end-to-end 5G slice models
- **Resource Allocation Algorithm:** Using Lagraingian primal-dual algorithm coupled with gradient descent for fast, near-optimal resource scaling under QoS constraints

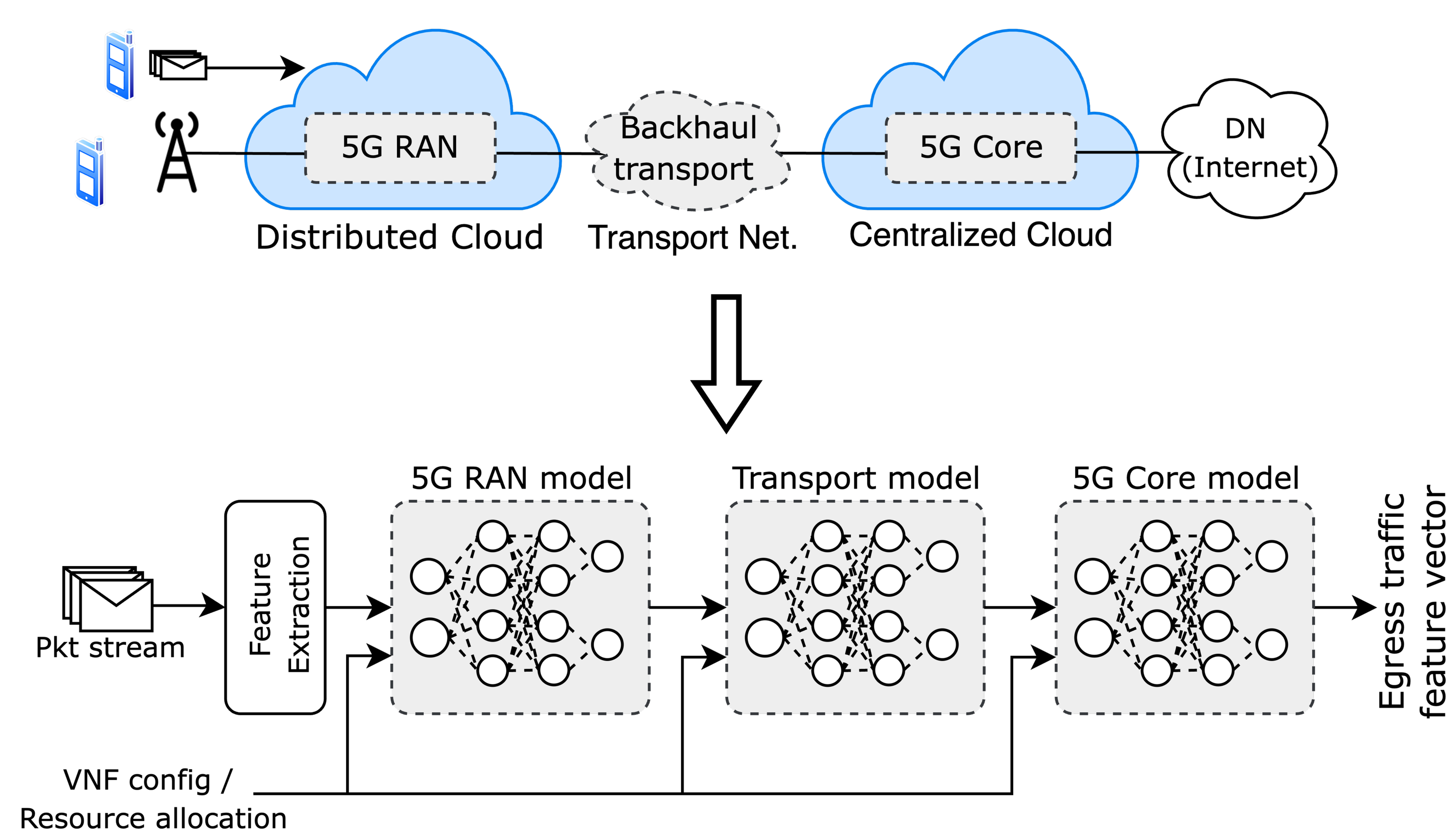
ML-BASED VNF & SLICE MODELING

VNF MODELING

- **Input/Output:** Predicts the egress traffic feature vector given input traffic trace (i.e., pcap) and VNF configuration & resource allocation
- **Dataset:** Uses data from in-lab 5G testbed and partner network operator's real network for training VNF models
- **Differentiability:** Leverages reparameterization trick to maintain VNF model differentiability
- **Composability:** Allows stacking VNF models to form end-to-end slice model

SLICE MODELING

- **Construction:** Composed using individual VNF models



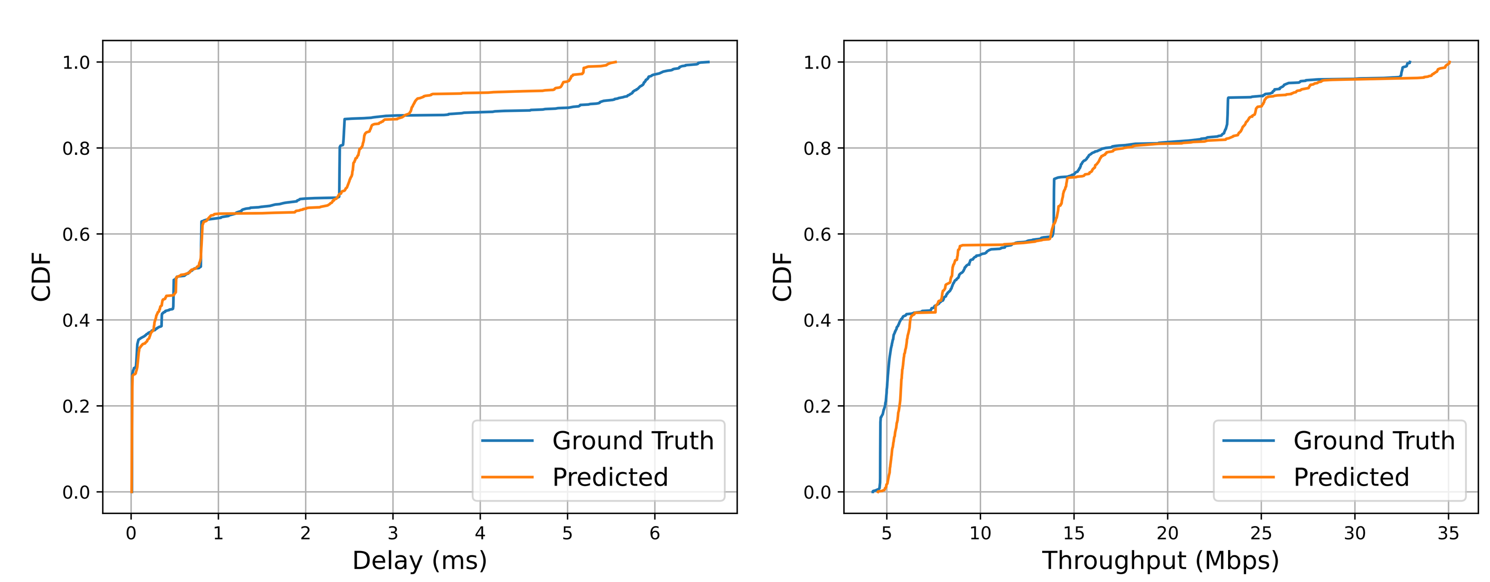


Fig: Ground truth vs. predicted throughput and delay for end-to-end slice model

RESOURCE ALLOCATION ALGORITHM

ALGORITHM

- **Lagrangian primal dual algorithm coupled with Gradient descent**
  - **Relaxed Lagrangian formulation:**

    $$\mathcal{L} = \boldsymbol{r} + \boldsymbol{\lambda} \cdot (QoS_{required} - QoS_{predicted})$$

  - **Outer loop:** Updates Lagrangian variables ($\boldsymbol{\lambda}$) based on QoS constraint violation (i.e., $QoS_{required} - QoS_{predicted}$)
  - **Inner loop:** Utilizes gradient descent to minimize the relaxed Lagrangian, with gradients from the differentiable slice model

Algorithm 1 MicroOpt Algorithm

Input: Traffic $\boldsymbol{x}_i^s$, Slice Model $f_{QoS}^s(\boldsymbol{x}_i^s, \boldsymbol{r}_i^s)$, QoS threshold q_{thresh}^s, QoS degradation threshold β_{thresh}^s, $\tau_{1,max}, \tau_{2,max}, \alpha_1, \alpha_2, \alpha_3, \epsilon_1, \epsilon_2$

Output: Optimal resource allocation vector $\boldsymbol{r}_i^s$

```
Initialize λ, μ, LB = 0, UB = ∞, τ1 = 0, τ2 = 0
while (UB−LB)/UB > ε1 or τ1 < τ1,max do            ┐ Outer loop
    r ← Initialization(x_i^s, f_QoS(x_i^s, r))     │
    while |∇_r L̂| > ε2 or τ2 < τ2,max do           │ ┐ Inner loop
        r ← [r − α1 ∇_r L̂]^+                        │ │
        τ2 ← τ2 + 1                                  │ ┘
    end while                                        │
    λ_s ← [λ_s + α2(β_i^s − β_thresh^s)]^+, ∀s       │
    μ_k ← [μ_k + α3(Σ_{s∈S} r^{s,k} − R^k)]^+, ∀k    │
    LB = max(LB, L(r, μ, λ))                         │
    UB = min(UB, Σ_{s∈S} η^T r^s)                    │
    τ1 ← τ1 + 1                                      ┘
end while
return r
```

RESULTS

- **Resource saving:**
  14.60% and 20.74% improvement over previous SOTA and peak resource allocation
- **Significantly faster resource scaling:**
  2-3 orders of magnitude faster resource scaling compared to previous SOTA