Dynamic Learning-based Link Restoration in Traffic Engineering with Archie

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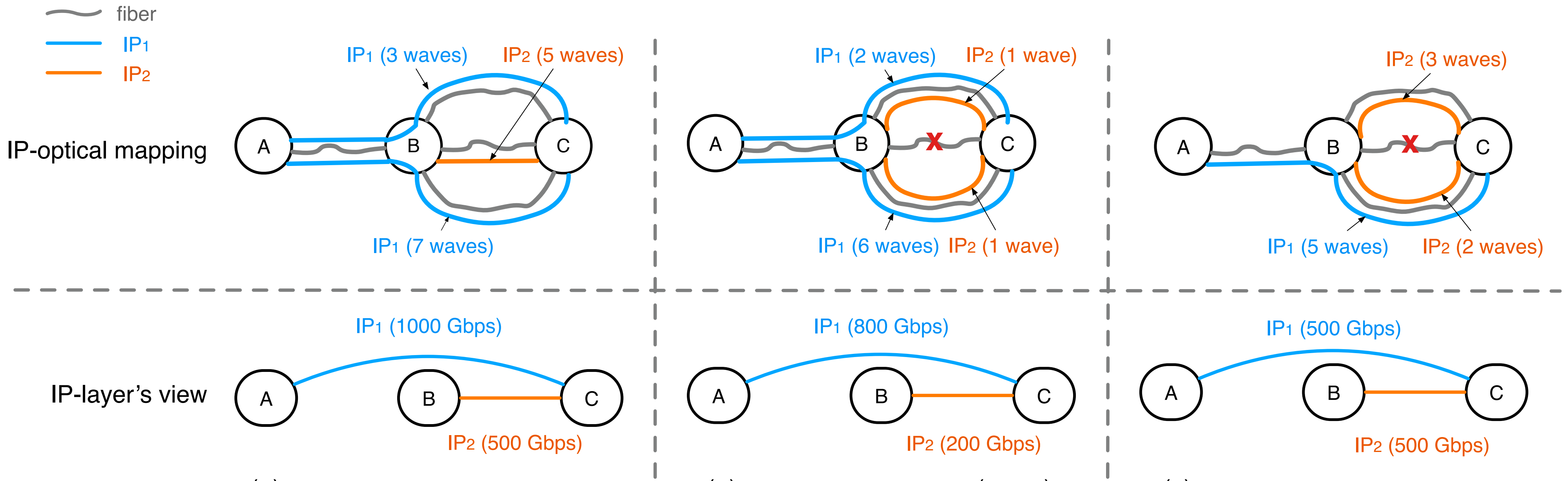
Optical Restoration in Wide-Area Networks (WANs)



(a) Original mapping (healthy state) (b) Restoration candidate (ticket) 1 (c) Restoration candidate (ticket) 2

* 1 wave = 100 Gbps

* Each restoration candidate is recorded as a restoration ticket

- IP layer in WAN is constructed through IP-optical mapping
- When there is a fiber cut, there are many partial restoration candidates
- Traffic is routed on the IP layer in WAN

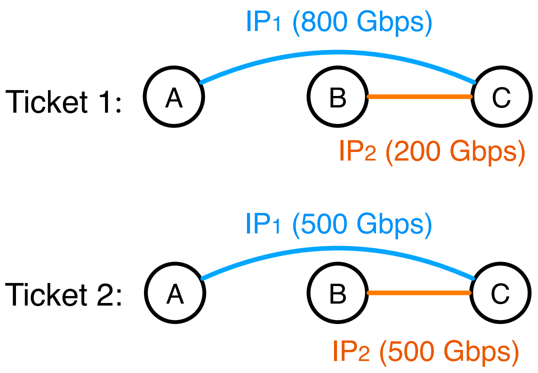
Best Restoration Ticket Selection Depends on Traffic Demand

- <u>Which restoration candidate (ticket) leads to highest throughput?</u>

Demand 1

A —> C: 700 Gbps

B —> C: 100 Gbps



Throughput 1

Ticket 1: 700 + 100 = 800 Gbps

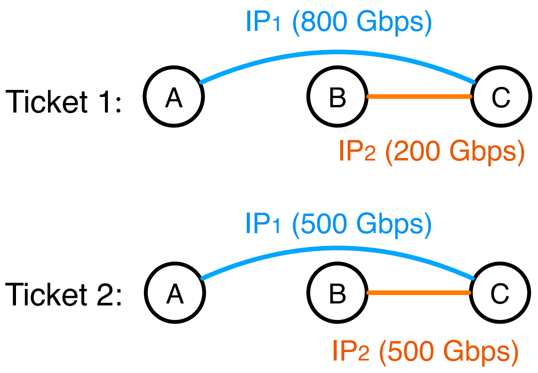
Ticket 2: 500 + 100 = 600 Gbps

Ticket 1 is better

Demand 2

A —> C: 300 Gbps

B —> C: 500 Gbps



Throughput 2

Ticket 1: 300 + 200 = 500 Gbps

Ticket 2: 300 + 500 = 800 Gbps

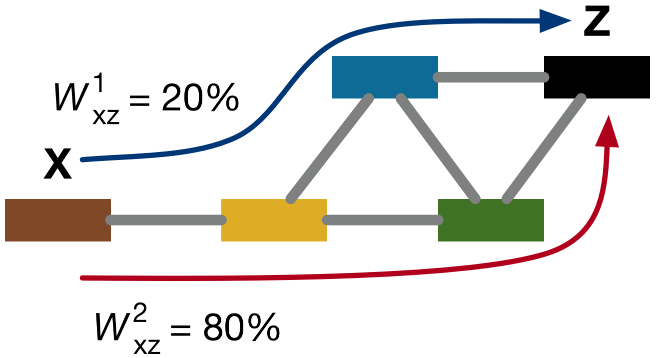
Ticket 2 is better

Existing Work: Candidate Ticket Set + Traffic Engineering (TE)

- Within a fixed IP-layer view, a flow (src-dst pair) can be routed among different candidate paths.
- The possible maximum throughput can be formulated as TE optimization formulation.

Determination Variable

W_f^k : traffic fraction of flow *f* on path *k*



Demand for flow *f*

$$\max \sum_f \sum_k w_f^k D_f$$ → Maximize throughput

$$\text{s.t.} \sum_k w_f^k \le 1, \forall f,$$
$$w_f^k \ge 0, \forall f, k,$$
→ Allocate non-negative traffic and total traffic assigned cannot exceed flow's demand

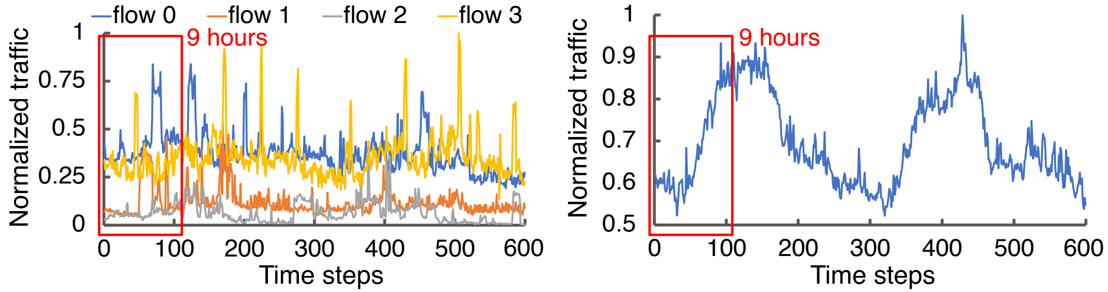
$$\sum_f \sum_k P_e^k w_f^k D_f \le C_e, \forall e.$$ → Aggregated traffic on each Link does not exceed its capacity

Whether link *e* on path *k* Capacity of link *e*

- Arrow (Sigcomm'21) select the best ticket by *formulating TE* on *different restoration tickets* and select the best with highest throughput using **instantaneous traffic** when fiber is cut.

New Question: Ticket Selection for the Long Run

- Fiber cut always take long to repair (9 hours on average (Arrow Sigcomm'21))
- **Challenge 1: Traffic dynamics** in fiber repair time



(a) Traffic on 4 selected flows

(b) Sum of the traffic on all flows

- **Challenge 2: Reconfiguration Overhead**
  - Reconfiguring wavelengths takes non-negligible time
    - At least $O(10)$ seconds with the latest hardware on a simple 4-node topology (Arrow Sigcomm'21)

Static Restoration: Calculate one ticket with traffic at fiber cut and use it for the whole repair time. ?

Constant Restoration: Change ticket every TE time step to cope with dynamic traffic. ?

Extreme ticket selection methods may lead to throughput loss

- **Balance traffic dynamic and reconfiguration overhead:** select restoration tickets every T time steps. (T is a short period (e.g. T=10) compared with whole repair time)

Strawman Solution for *T*-Step Ticket Selection

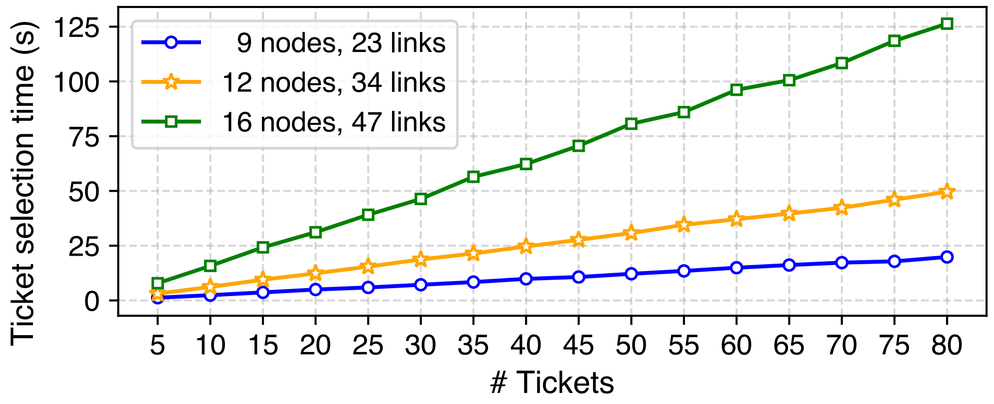
- Strawman solution: Demand Prediction

Demand prediction: Predict demand of next T steps	→	Solve TE for each ticket: Solve TE with predicted demand for next *T* steps*	→	Calculate total throughput for each ticket: Sum up throughput of *T* steps	→	Ticket selection: Select ticket with maximum throughput

- Backwards of Demand Prediction:

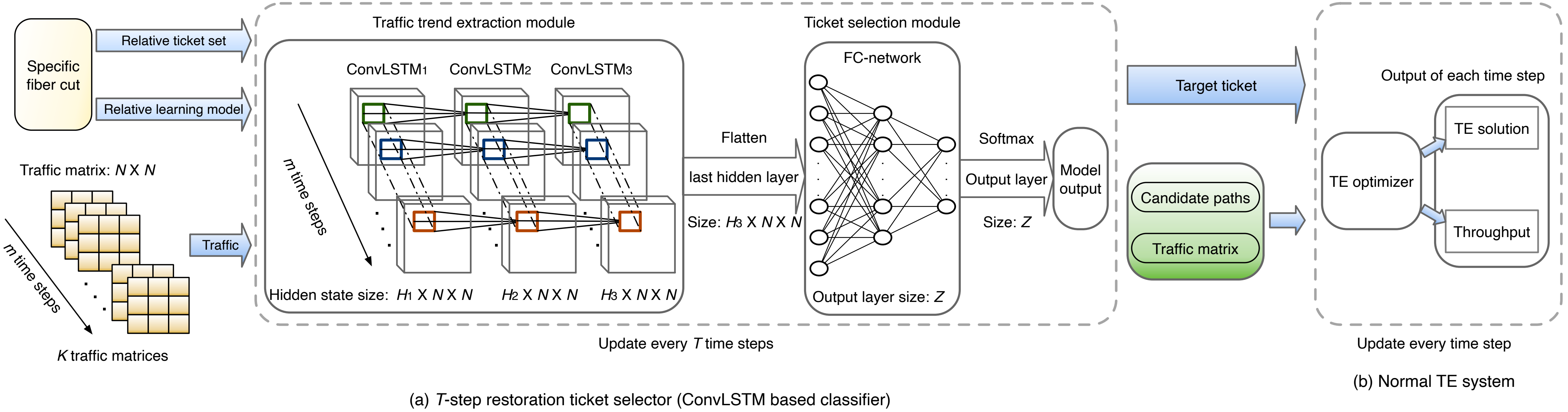
  1. Time consuming
  - Requires to solve TE for TZ times (Z is the number of candidate tickets) to select one ticket.

  2. Prediction inaccuracy
  - Traffic prediction will be inaccurate for the long horizon even with state-of-the-art learning methods.



* Current TE always predict traffic 1-step ahead (Smore NSDI'18), we extend it to prediction of *T* steps.

Our Design: Archie, An End-to-End Learning-Based Method



- Models are *trained* ***offline*** and only conduct *inference* ***online***.
- **Label generation** of *supervised learning*: Using the actual traffic demand of next T steps.

Intuitive advantages of Archie:

1. **Faster decision time**: one pass of the model inference instead of solving TE optimizations TZ times.
2. **Robust to inherent prediction inaccuracy**: end-to-end learning copes with traffic uncertainties as long as the selected ticket is correct, instead of requiring accurate demand prediction for all T steps.
   - We will show insights why Archie outperforms Demand Prediction with analysis evaluation afterwards.

Evaluation Setups

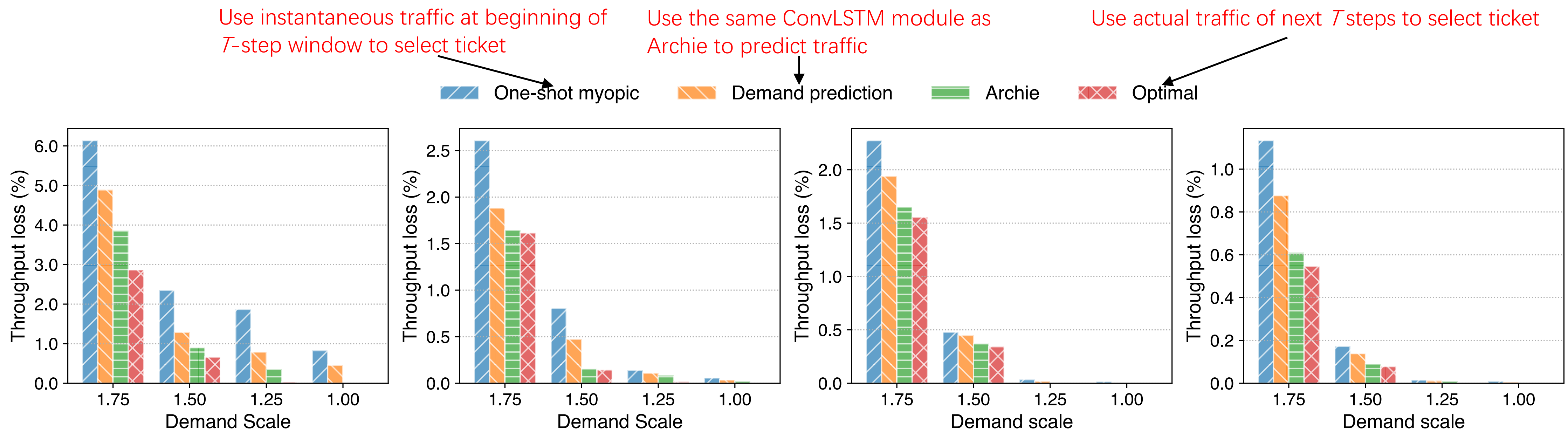
- Evaluated topologies and traffic traces

Topology	# Nodes	# Fibers	# IP links	# Traffic matrices (Train + Test)
Arpanet	9	10	23	2880+120
Abilene	12	15	34	
Airtel	16	26	47	
GRnet	37	42	101	

- Evaluation setups
  - *Ticket setup:* Z=30 by default for each fiber cut scenario
  - *TE setup:* K=4 shortest path for each flow, one time step is 5 minute
  - *Fiber cut scenario:* Random one fiber cut

Performance of Archie: Throughput Loss

- Settings: *T* is fixed to be 10, reconfiguration overhead is not considered currently.



(a) Arpanet (b) Abilene (c) Airtel (d) GRnet

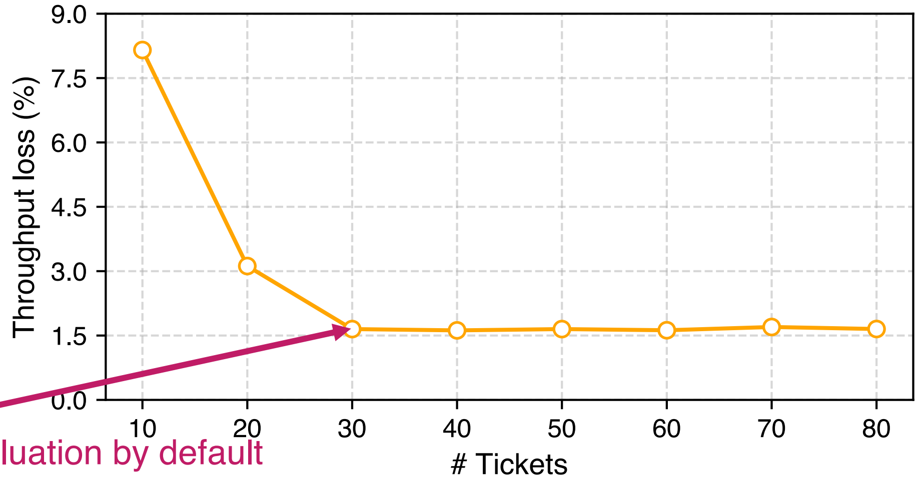
- Near-to-optimal performance: additional throughput loss only range from 0% to 0.98% at most.
- Reduce 48.5% and 27.1% throughput loss compared to One-shot myopic and Demand prediction, respectively.
- Performance are robust to all demand scales and topology scales.

Performance of Archie: Ticket Selection Time

Topology	T	Ticket selection time (seconds)		
		One-shot myopic	Demand prediction	Archie
Arpanet	5	0.729	3.644	0.01875
	10	0.721	7.102	0.01900
	15	0.732	10.982	0.01894
Abilene	5	1.845	9.221	0.02544
	10	1.852	18.001	0.02501
	15	1.847	27.705	0.02539
Airtel	5	4.746	23.712	0.03011
	10	4.745	48.003	0.02996
	15	4.751	71.265	0.03008
GRnet	5	51.974	259.182	0.04355
	10	52.123	522.313	0.04441
	15	51.988	779.320	0.04483

- Neat-to-zero selection time: within 45ms in all our test cases.
- Speedups are 362x and 3598x compared to One-shot myopic and Demand prediction on average.
- Good scalability: Growth speed of decision time in Archie is slow when the topology scales.

Performance of Archie: Candidate Ticket Number



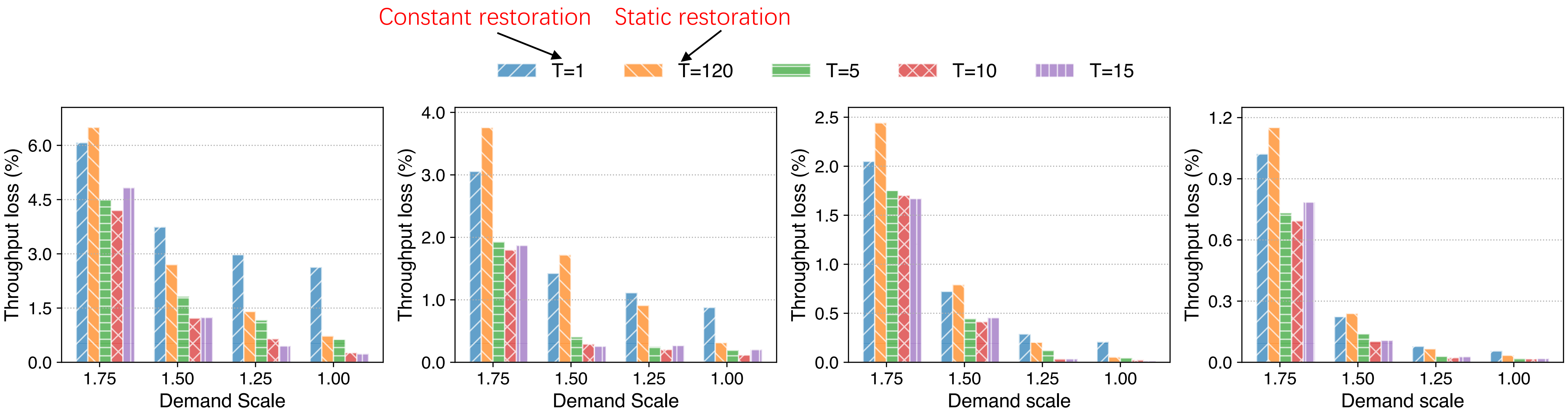
Elect 30 candidate tickets in evaluation by default

- In Abilene topology

- When tickets are not enough (≤ 30), ticket set may not cover a good ticket, adding tickets may improve performance.
- When exceeding 30 tickets, performance stop improving obviously. More tickets increase burden of model preparation.

Benefit of *T*-Step Dynamic Restoration

- Settings: Reconfiguration time is set to be 1/30 steps (10s).

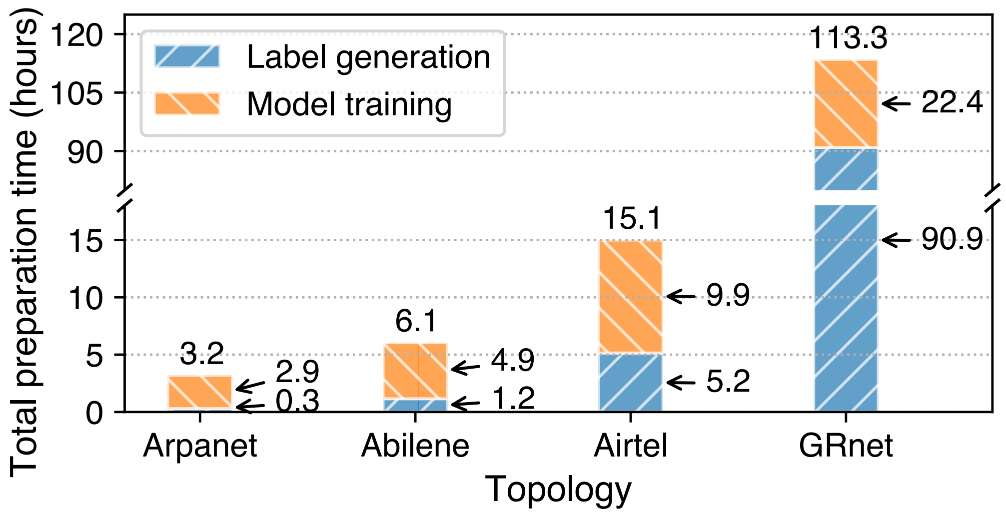


(a) Arpanet (b) Abilene (c) Airtel (d) GRnet

- Archie under best *T* reduce throughput loss by 64.7% and 59.6% compared to constant and static restoration.
- Archie with there moderate settings of *T* (5, 10, 15) has small performance difference less than 0.2%.

Offline Model Preparation Time of Archie

- Settings:
  - $T = 10$, $Z = 30$, concurrent threads $P = 192$ for generating $O(1000)$ labels. Needs $O\left(\frac{1000TZ}{P}\right)$ times TE solving.
  - One GPU for model training for all one fiber cut scenarios.



- Offline time investment is acceptable for real-world use:
  - Common medium topology (Abilene) can finish preparation within 6 hours.
  - Large topology (GRnet) can finish within 5 days.
- Time can be further reduced by leveraging more GPUs and concurrent threads to *enhance parallelism*.

Insight from Archie: Spatial Feature Analysis

Spatial Feature: Does Archie pay more attention to specific flows?

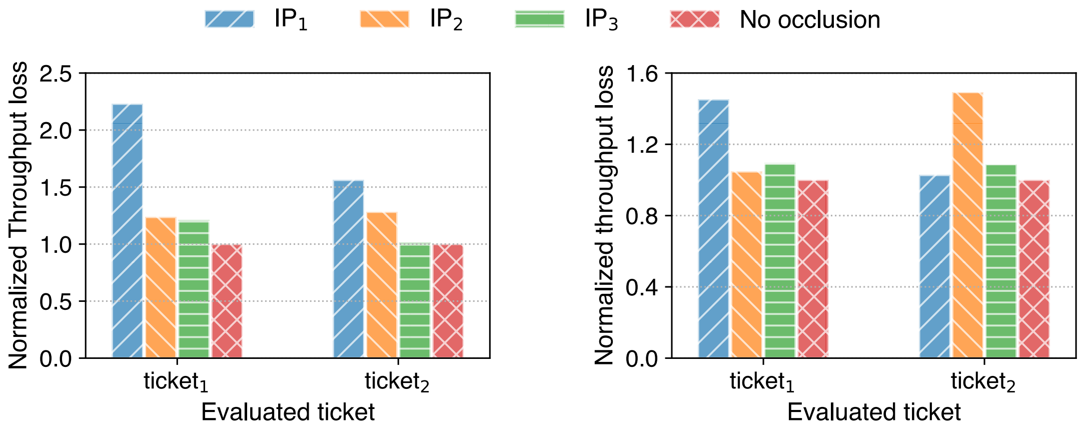
- **Method: Occlusion analysis** (Occludes evaluated traffic input part and evaluate the performance gap)
  - Clear demand to 0 for occluded flows.

- Evaluate traffic epochs whose ground truth is the following tickets.
- Occlude all flows traversing some links in the topology (IP1, IP2, IP3), respectively.

Topology	Information item	ticket_1			ticket_2		
		IP_1	IP_2	IP_3	IP_1	IP_2	IP_3
G_1	# Wavelengths	4	1	1	3	2	1
G_2	# Wavelengths	8	2	2	2	8	2

- Ticket Selection: occluded past traffic
- Throughput Calculation: original future traffic

- Performance Result of Occlusion



(a) Topology G_1 (b) Topology G_2

- For ticket 1 in G1, Traffic flows traversing IP1 are the more important than others (in future traffic).
- Archie assign more restored wavelengths to the corresponding links of the flows.

- Archie can identify parts of critical future flows, thus assign more restored wavelengths to corresponding links.

Insight from Archie: Spatial Feature Analysis

Spatial Feature: Does Archie's ability to identify critical flows makes it superior to Demand Prediction?

- Introduce the same flow importance in Archie to Demand Prediction.
  - Modify the MSE loss when training:

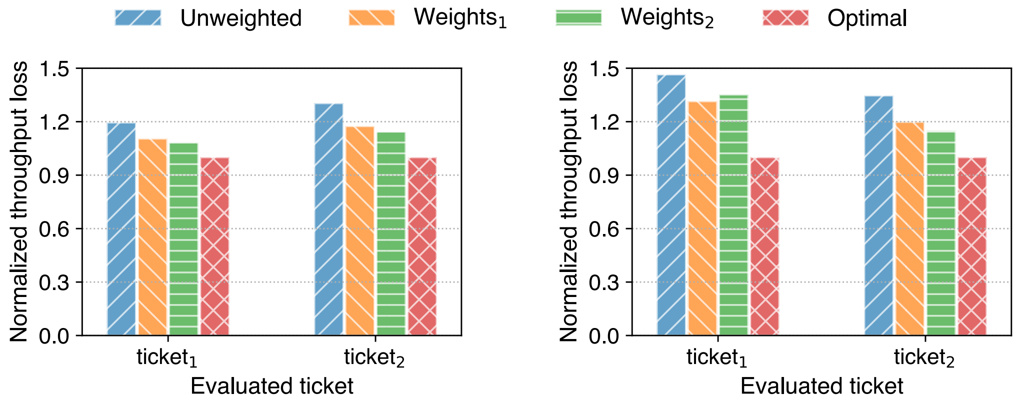
$$J = \frac{1}{T \times F} \sum_{t}^{T} \sum_{f}^{F} \alpha_f (y_{ft} - h_{ft})^2$$

  - Traditional MSE: α_f=1 for all flow *f*. (Unweighted)

- Weight assignment example

Topology	Information item	ticket_1			ticket_2		
		IP_1	IP_2	IP_3	IP_1	IP_2	IP_3
G_1	# Wavelengths	4	1	1	3	2	1
	Weights_1 (α_f)	2.0	1.0	1.0	2.0	1.5	1.0
	Weights_2 (α_f)	3.0	1.0	1.0	3.0	2.0	1.0
G_2	# Wavelengths	8	2	2	2	8	2
	Weights_1 (α_f)	2.0	1.0	1.0	1.0	2.0	1.0
	Weights_2 (α_f)	3.0	1.0	1.0	1.0	3.0	1.0

- Performance Result



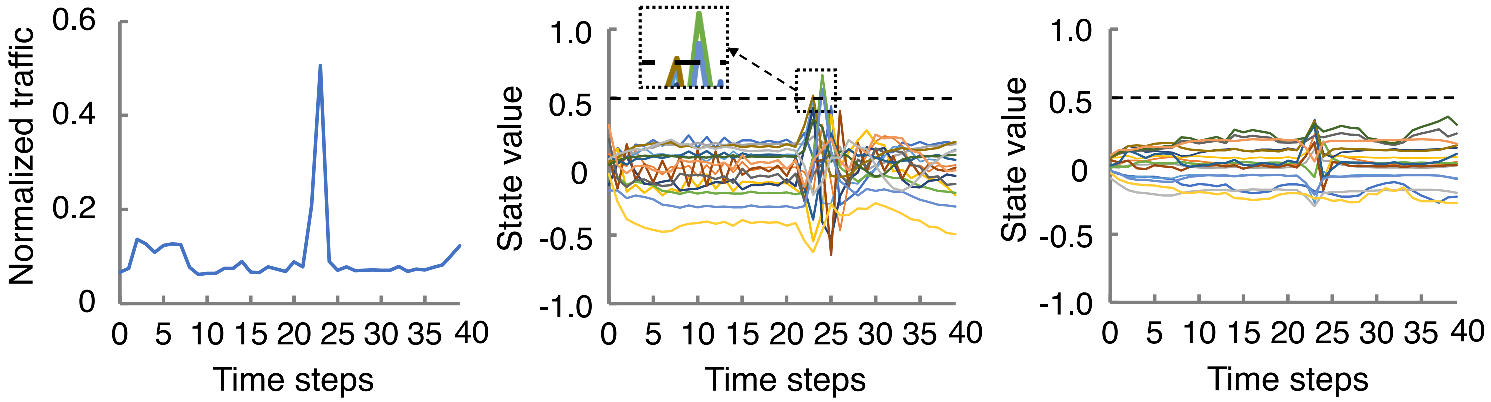
(a) Topology G_1 (b) Topology G_2

- Archie's ability to identify critical future flows is one of the reasons why it outperforms Demand prediction.
  - Performance: Optimal > Weight 1, Weight 2 > Unweighted

Insight from Archie: Temporal Feature Analysis

Temporal Feature: Does Archie identify to any special traffic patterns?

- Method: LSTMVis (check important time interval)



(a) Traffic demand (b) States of Archie (c) States of Demand Prediction

Interval from 20 to 25 has a traffic spike

Archie pays attention to this traffic spike

Demand Prediction does not

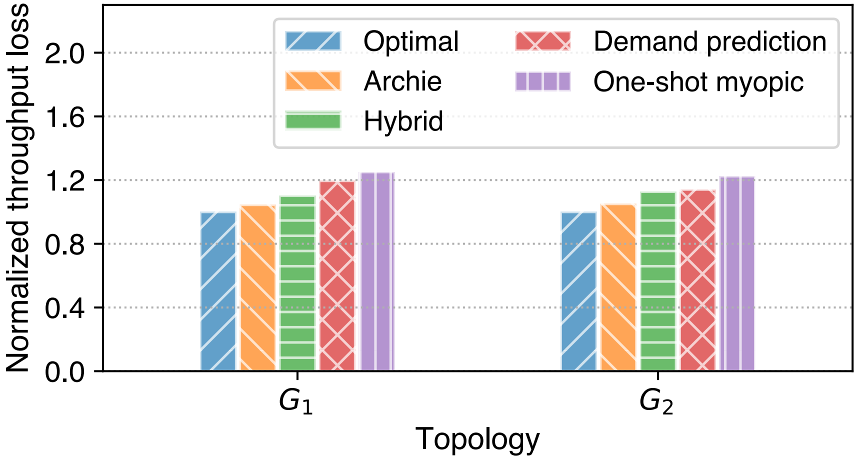
- Input past traffic length: 40
- Hidden states dimension of ConvLSTM: 16

- Archie can identify traffic spikes!

Insight from Archie: Temporal Feature Analysis

Temporal Feature: Does this traffic spike feature help ticket selection?

- Evaluate the performance without spike identification feature for Archie
  - Use ConvLSTM module parameters in Demand Prediction for Archie and freeze these parameters.
  - Retrain FC network in Archie to obtain a new model, it is called ***Hybrid***.



- Traffic spike feature in Archie does help ticket selection
  - **Archie outperforms Hybrid:** Identify traffic spikes
  - **Hybrid outperforms Demand Prediction:** Archie has other advantages for ticket selection (Identify vital flows).

Thank you!

Q&A