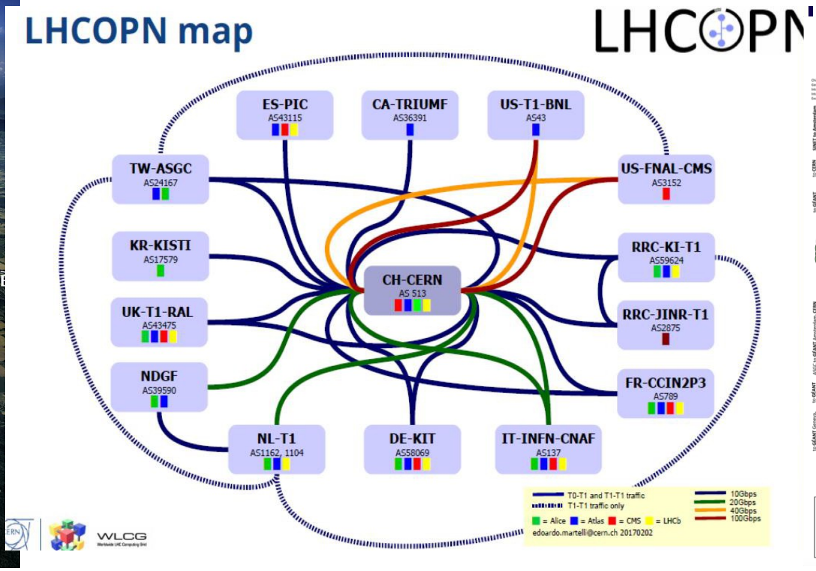
ALTO Integration and Implementation Supporting CERN Data Management (FTS/Rucio Integration)

Presenters: Jordi Ros Giralt, Mario Lassnig, Mihai Patrascoiu, Y. Richard Yang
On behalf of team (Jensen Zhang, Kai Gao, Lauren Delwiche, Mahdi , Ryan Yang)

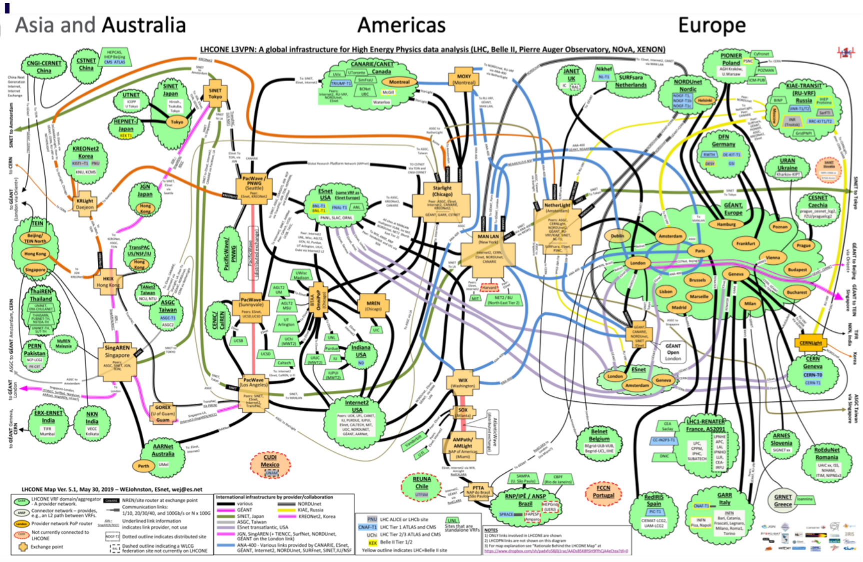
March 27, 2023

IETF 116

Overview: LHCONE



LHCONE



- Part of CERN infrastructure (experimental facilities, LHCOPN, LHCONE)
- Topology: 600 distributed storage systems, distributed globally (170 data centers, in 127 sites, across 40 countries)
- Workload: support data movement for four LHC experiments, and also Belle II, Pierre Auger Observatory, NOvA, XENON, and JUNO
- Traffic: 2022, the aggregated outgoing traffic just from CERN to its ten largest connected data centres: 457 Petabytes of data.

Overview: Related Software Stack

Data-Intensive Workflows

Data Management / Transfer Orchestration
(e.g., Rucio)

Data Transfer Scheduling
(e.g., FTS)

Transfer Data Plane
(e.g., GridFTP, XRootD, HTTP)

Internet Transport Layer
(e.g., TCP, TCP/Cubic, BBR)

Networking Layer (e.g., traditional networking,
AutoGOLE/SENSE, NOTED, Programmable net)

Our focus

High-level goals:
- **Efficiency**
- **Fairness**

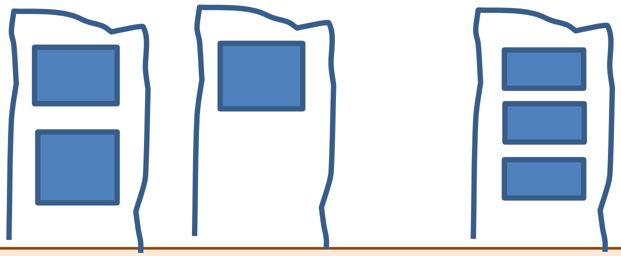
Outline

- Overview
- Transport scheduling integration (ALTO/FTS)

Transfer Scheduling (FTS): Objective and Design

Related objectives:

- Efficiency control: Avoid overloading transfer resources (both network and storage), fully utilize all capacity
- Fairness/allocation: resource allocation beyond congestion



Mechanisms:

- Keeps transfer queue for each src/dst pair (pipe)
- Adjusts # concurrent TCP connections per pipe
- Dispatches transfer if allowed by concurrency level

New but not fully integrated mechanisms:

- Each file transfer (src->dst) is marked as on behalf of an activity of an experiment

Data-Intensive Workflows

Data Management / Transfer Orchestration (e.g., Rucio)

Transfer Scheduling (e.g., FTS)

Transfer Data Plane (e.g., GridFTP, XRootD, HTTP)

Internet Transport Layer (e.g., TCP, TCP/Cubic, BBR)

Networking Layer (e.g., traditional networking, AutoGOLE/SENSE, NOTED, Programmable net)

ALTO/FTS Objective: Application-Defined Networking

Diverse, High Level Resource Models

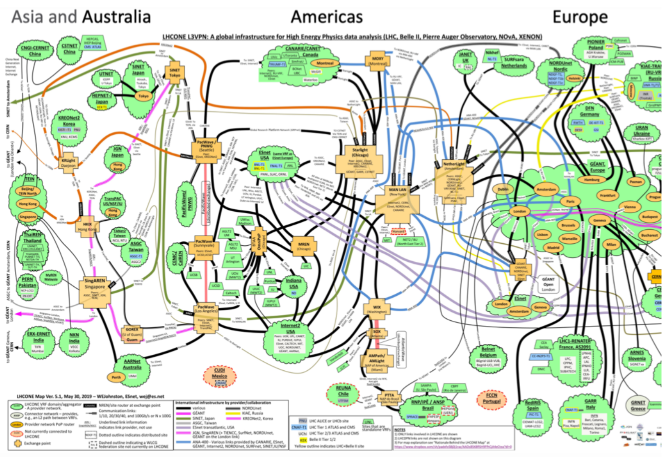
ALTO/FTS Scheduler

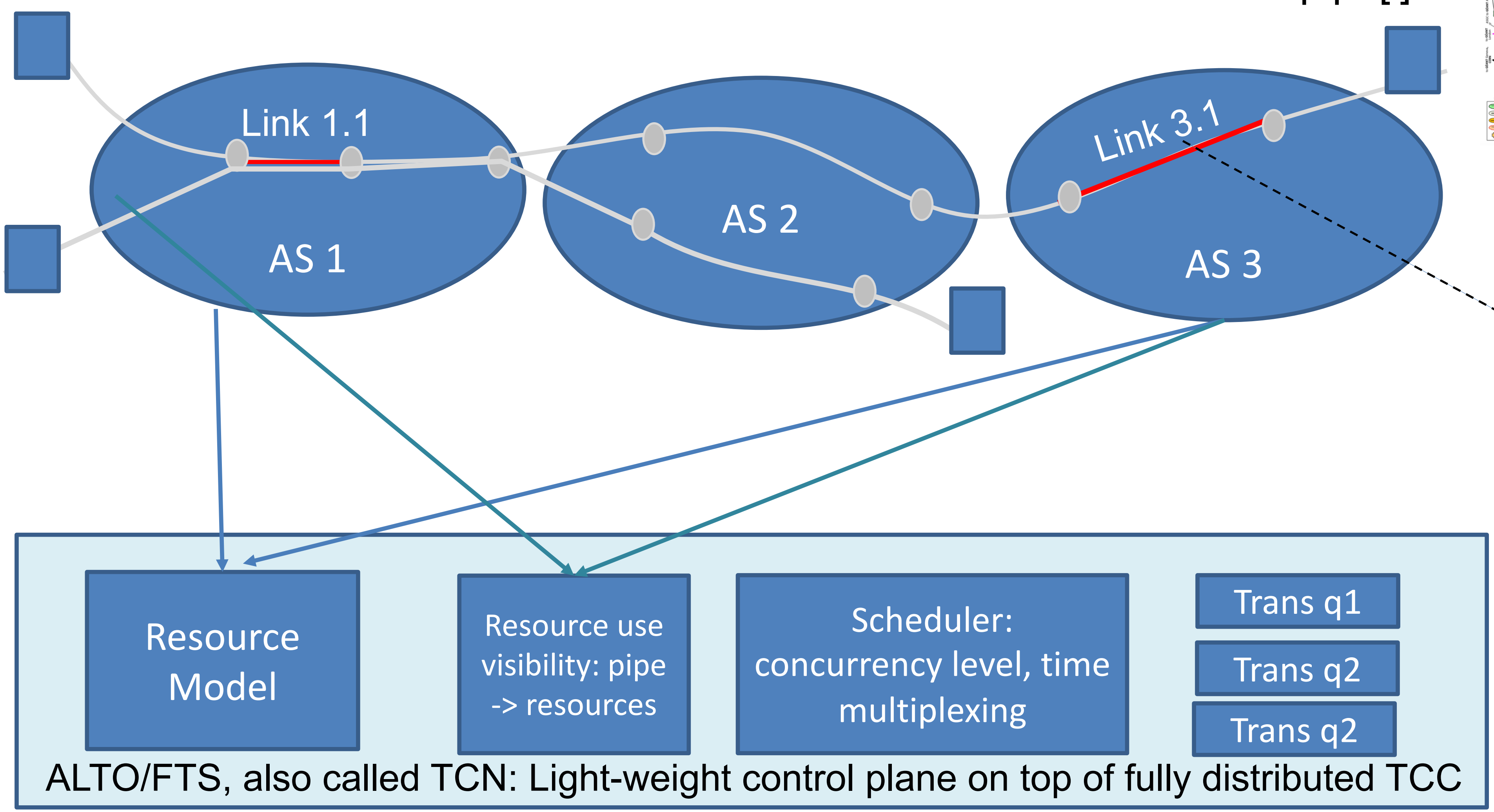
Universal, Minimal TCP Congestion Control (TCC)

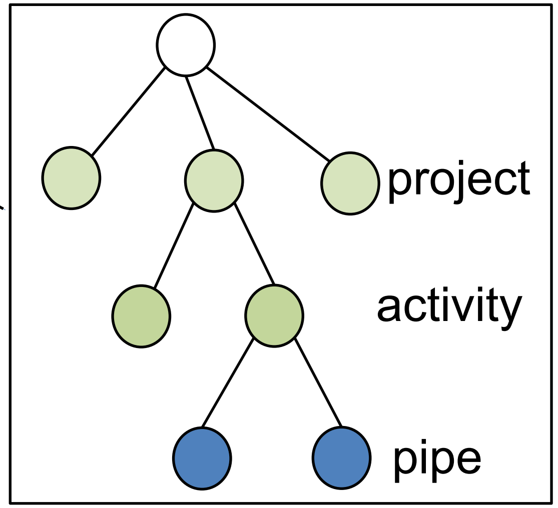
- **Universally** available
- **Fast, efficient, robust** building block
- But **single** resource allocation (fairness) model

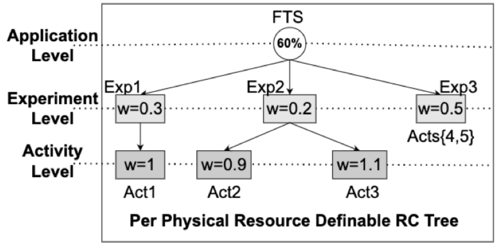
Diverse Network Settings

ALTO/FTS Architecture









Simplified Example Illustrating ALTO/FTS Visibility, Control

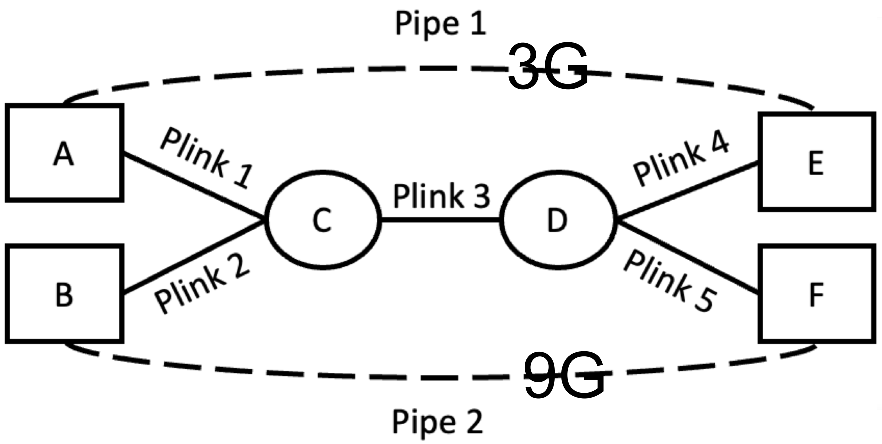
Resource Model:

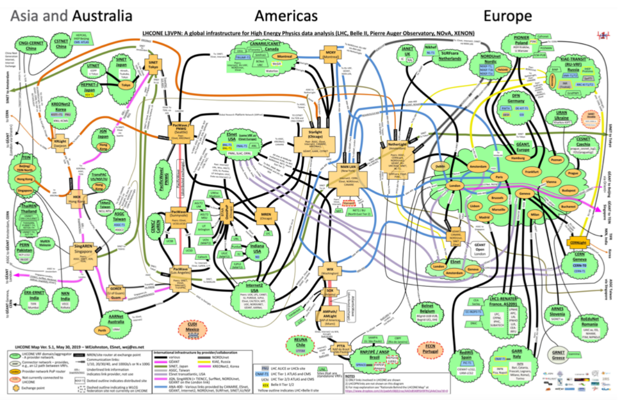
Project 1 pipes: Pipe 1, Pipe 2

R1: <Project 1, Plink 1> <= 5G

R2: <Project 1, Plink 2> <= 10G

R3: <Project 1, Plink 3> <= 10G





App Provided State:

Pipe1.traffic = 3G, Pipe2.traffic = 9G

ALTO Provided State:

Pipe 1: {Plink 1, Plink 3, Plink 4}.

Pipe 2: {Plink 2, Plink 3, Plink 5}.

Resource use by project on physical resources:

Plink1.traffic = 3G, Plink2.traffic = 9G,

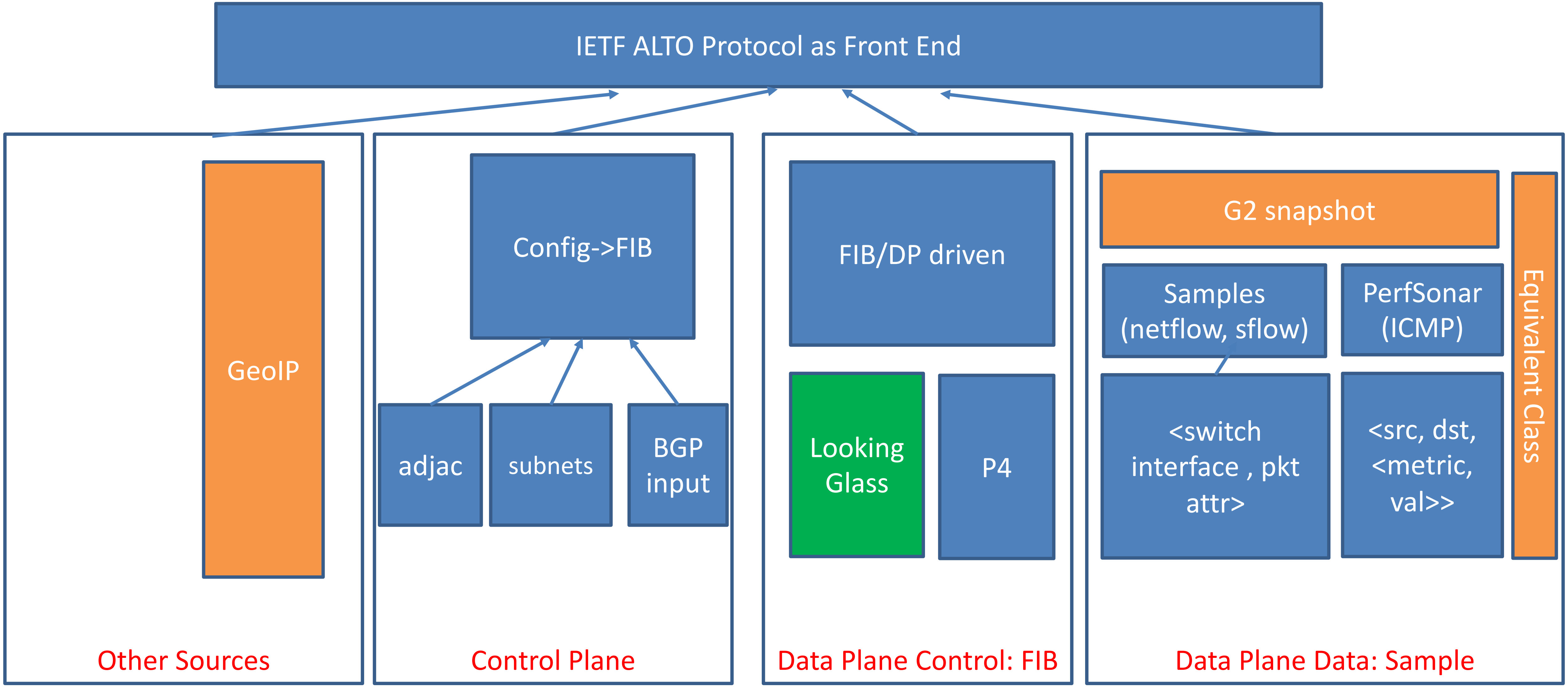
Plink3.traffic = Pipe1.traffic + Pipe2.traffic = 12G

Penalty for resource control constraints:

P(R1) = 0 (Plink1 = 3G <= 5G) , P(R2) = 0 (Plink2 = 9G <= 10G)

P(R3) = 2 (Plink3 = 12G > 10G)

ALTO/FTS Visibility



ALTO/FTS First Hop Visibility

Query Example (ECS with path vector extension)

Query/Response

```
→ cat request-cern.json
{
  "cost-type": {
    "cost-metric": "ane-path",
    "cost-mode": "array"
  },
  "endpoint-flows": [
    {
       "srcs": [ "ipv4:137.138.0.101" ],
       "dsts": [ "ipv4:134.158.84.23", "ipv4:144.16.112.112" ]
    },
    {
       "srcs": [ "ipv4:192.16.166.254" ],
       "dsts": [ "ipv4:140.115.32.101" ]
    }
  ],
  "ane-property-names": [ "next_hop", "as_path" ]
}
```

```
→curl -s -H 'Content-Type: application/alto-endpointcostparams+json' --data-ascii @
request-cern.json https://science.jensen-zhang.site/pathvector/cern-pv | ./pprint
--d41d8cd98f00b204e9800998ecf8427e
Content-Type: application/alto-endpointcost+json
Content-ID: <ecs@science.jensen-zhang.site>

{'endpoint-cost-map': {'137.138.0.101': {'134.158.84.23': ['autolink_1',
                                                           'autopath_2'],
                                         '144.16.112.112': ['autolink_1',
                                                            'autopath_3']},
                       '192.16.166.254': {'140.115.32.101': ['autolink_1',
                                                             'autopath_1']}},
 'meta': {'cost-type': {'cost-metric': 'ane-path', 'cost-mode': 'array'},
          'vtag': {'resource-id': 'cern-pv.ecs',
                   'tag': 'e615bf984f7249949f8903c5cf56f02d'}}}
--d41d8cd98f00b204e9800998ecf8427e
Content-Type: application/alto-propmap+json
Content-ID: <propmap@science.jensen-zhang.site>

{'meta': {'dependent-vtags': [{'resource-id': 'cern-pv.ecs',
                               'tag': 'e615bf984f7249949f8903c5cf56f02d'}]},
 'property-map': {'.ane:autolink_1': {'next_hop': '192.65.184.145'},
                  '.ane:autopath_1': {'as_path': '20965 24167 7539 1659'},
                  '.ane:autopath_2': {'as_path': '20965 2091 789'},
                  '.ane:autopath_3': {'as_path': '20965 9885 55824'}}}
--d41d8cd98f00b204e9800998ecf8427e--
```

Routing Plane Retrieval (Looking Glass of CERN and GEANT)

Implementation

etc > {} lg-agent.json > ...

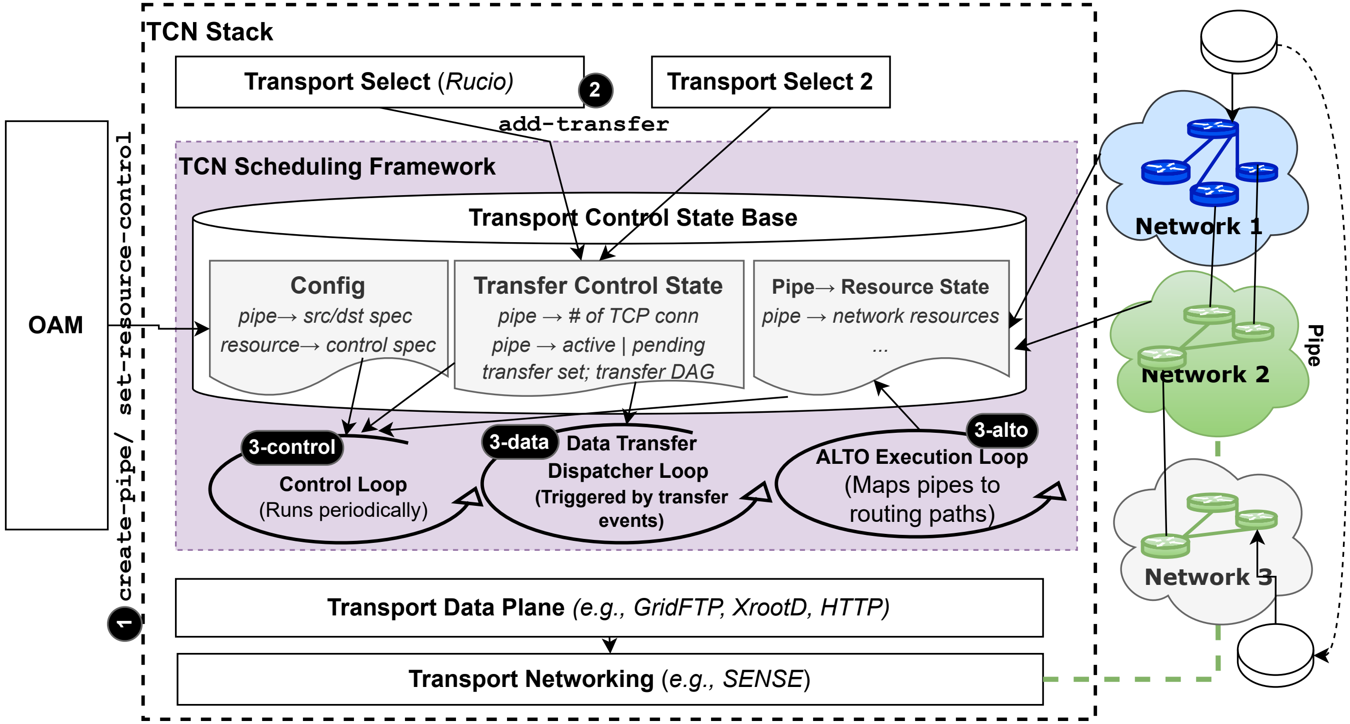
```
{
    "namespace": "default",
    "agent_class": "alto.agent.cernlg.LookingGlassAgent",
    "uri": "http://lhcone-lg.cern.ch/lg.cgi",
    "default_router": "ex2j.cern.ch:juniper",
    "refresh_interval": 300
}
```

Jensen/Kai/Lauren

ALTO/FTS Control Implementation

Integration into FTS 3.12

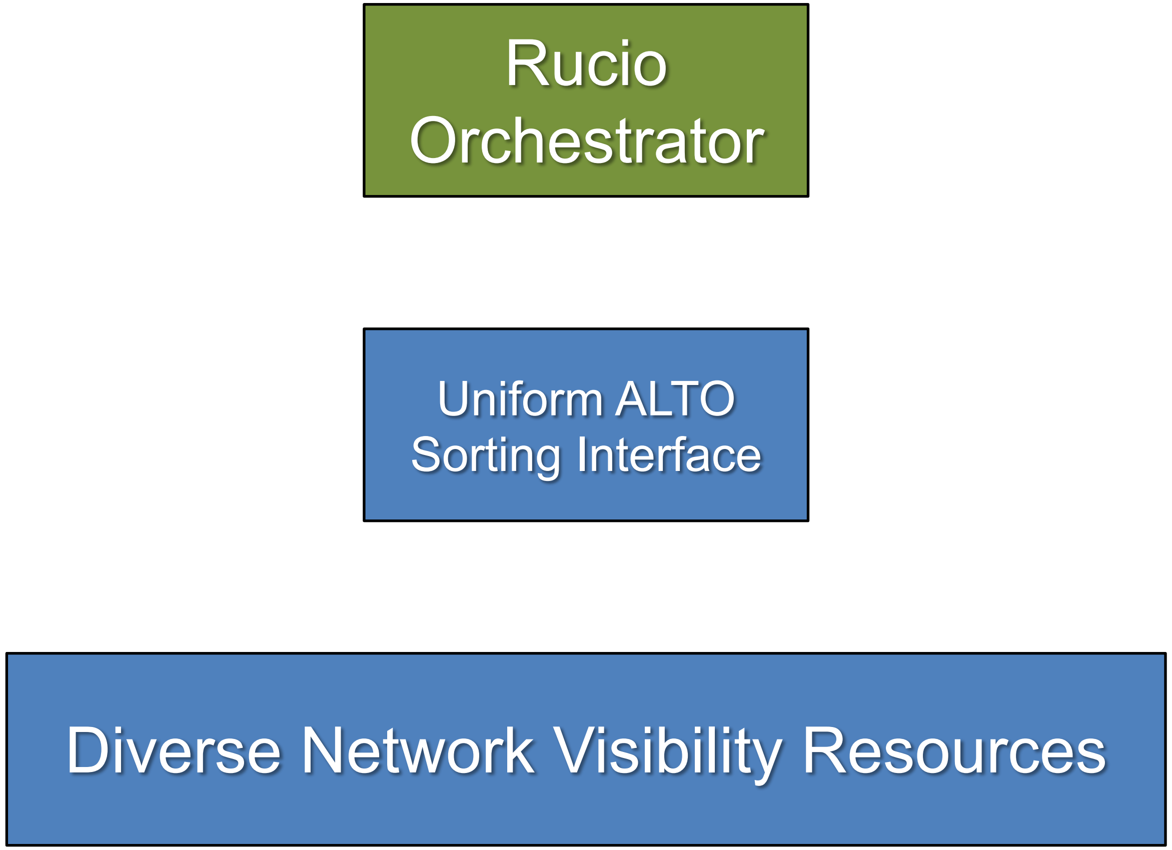
- Extend database schema for pipes (`t_link_config`) to support resource control specification (`tcn_abs_limit`, `tcn_rel_weight`)
- Implement `ALTO/TCNOptimizer` class for ALTO/TCN control loop
  - Implementing ZeroOrder Gradient with Integral, Quadratic Distance function
  - Add new optimizer mode (`kOptimizerAggregated`) to enable ALTO/TCN optimizer



Outline

- Overview
- Transport scheduling integration (ALTO/FTS)
- Transport orchestration integration (ALTO/Rucio)

ALTO/Rucio Objective: Uniform Orchestration Selection



ALTO/Rucio Using Query Expression

Step 1: Configuration

Configure ALTO client at Rucio server to fetch visibility using ALTO

```
[client]
# ALTO server
default_ird = https://science.jensen-zhang.site/directory/default
metrics = {
  "as_hopcount": {
    "resource_type": "path-vector",
    "resource_id": "cern-pv",
    "prop_name": "as_path",
    "prop_transformer": "tolist | len",
    "aggr_transformer": "sum"
  },
  "delay_ow": {
    "resource_type": "cost-map",
    "resource_id": "delay-ow",
    "dependent_network_map": "default-networkmap"
  }}
```

Map properties of ANEs into end-to-end metrics

Step 2: Express Sorting using ALTO/Rucio Expression

ALTO sorting expression enables Rucio download command to sort replicas based on a combination of distances and properties, e.g.,

BY=as_hopcount,delay_ow WHERE continent=”EU”

```
ainernet> rc rucio list-file-replicas --sort='alto;stmt="BY as_hopcount,delay_ow"' --metalink tes
l version="1.0" encoding="UTF-8"?>
alink xmlns="urn:ietf:params:xml:ns:metalink">
le name="file1">
dentity>test:file1</identity>
ash type="adler32">69fe2b13</hash>
ash type="md5">12969016e761864f30f97dd5fb259e30</hash>
ize>1048576</size>
lfn name="/atlas/rucio/test:file1"></glfn>
rl location="XRD1" domain="wan" priority="1" client_extract="false">root://xrd1:1094//rucio/test/
rl location="XRD3" domain="wan" priority="2" client_extract="false">root://xrd3:1096//rucio/test/
rl location="XRD4" domain="wan" priority="3" client_extract="false">root://xrd4:1097//rucio/test/
ile>
talink>
```

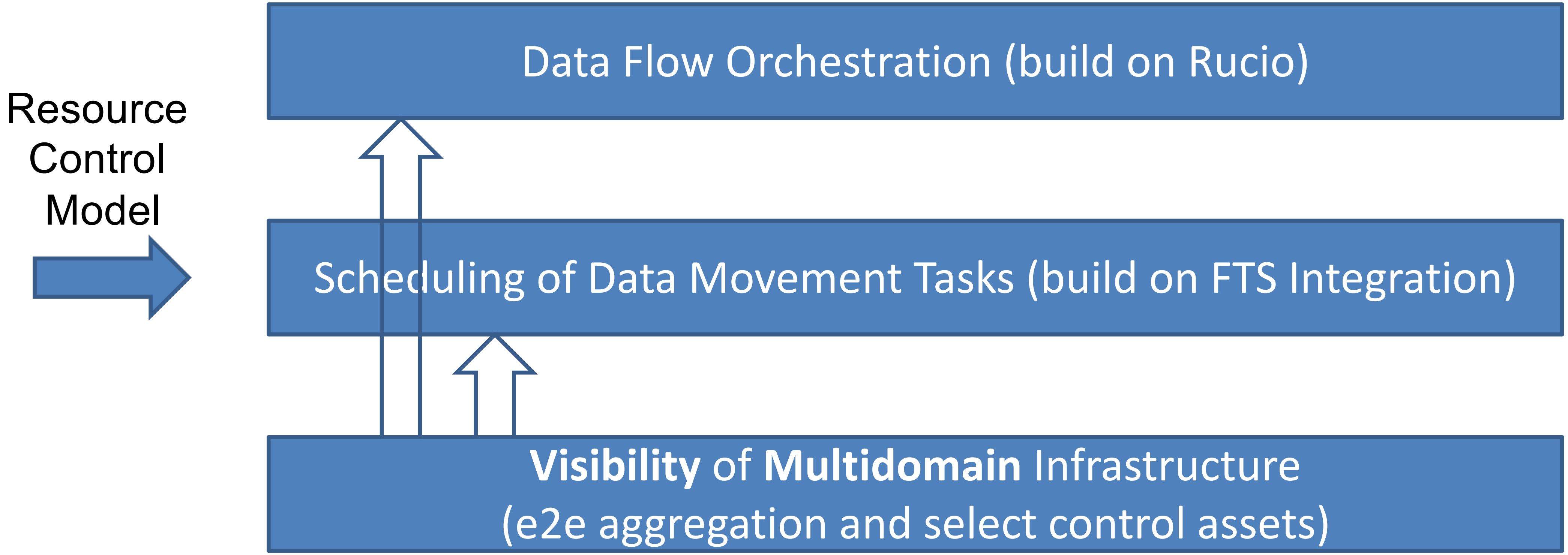
ALTO/Rucio Using Query Expression: Default/Backup GeoIP/Distance

- Providing geoip property using the standard ALTO endpoint property service **[RFC 9240]**
- Providing geo distance between endpoints using the standard ALTO Endpoint Cost Service (ECS) **[RFC 7285]**

```
➜curl -s -k -u cern:lhcone -H 'Content-Type: application/alto
-propmapparams+json' -d '{"entities":["ipv4:198.17.101.70"]}'
https://localhost:8443/entityprop/geoip | jq .
{
  "property-map": {
    "ipv4:198.17.101.70": {
      "geolocation": {
        "lat": 32.8515,
        "lng": -117.2798
      }
    }
  }
}
```

```
etc > {} geoip-delegate-agent.json > ...
{
    "namespace": "default",
    "agent_class": "alto.agent.delegate.DelegateAgent",
    "data_source_name": "geoip",
    "data_source_config": {
        "data_source_cls": "alto.agent.geoip.GeoipAgent",
        "db_path": "/opt/geoip2/GeoLite2-City.mmdb"
    },
    "refresh_interval": 300
}
```

Summary: Current ALTO/FTS+Rucio: 3 Main Components



Status and Next Steps

- Implementations
  - ALTO/FTS
    - Visibility: looking glass first-hop links (e.g., CERN border links to peers)
    - Control: Zero-order stochastic gradient algorithm, event-driven programming
    - Scale: 200x40, targeting 600x600 full mesh
    - Resource model: Full linear model
  - ALTO/Rucio
    - Fully integrated, uniform interface
- Deployment
  - Target full production workload in summer 2023, for HL-LHC Data Challenge

Backup Slides

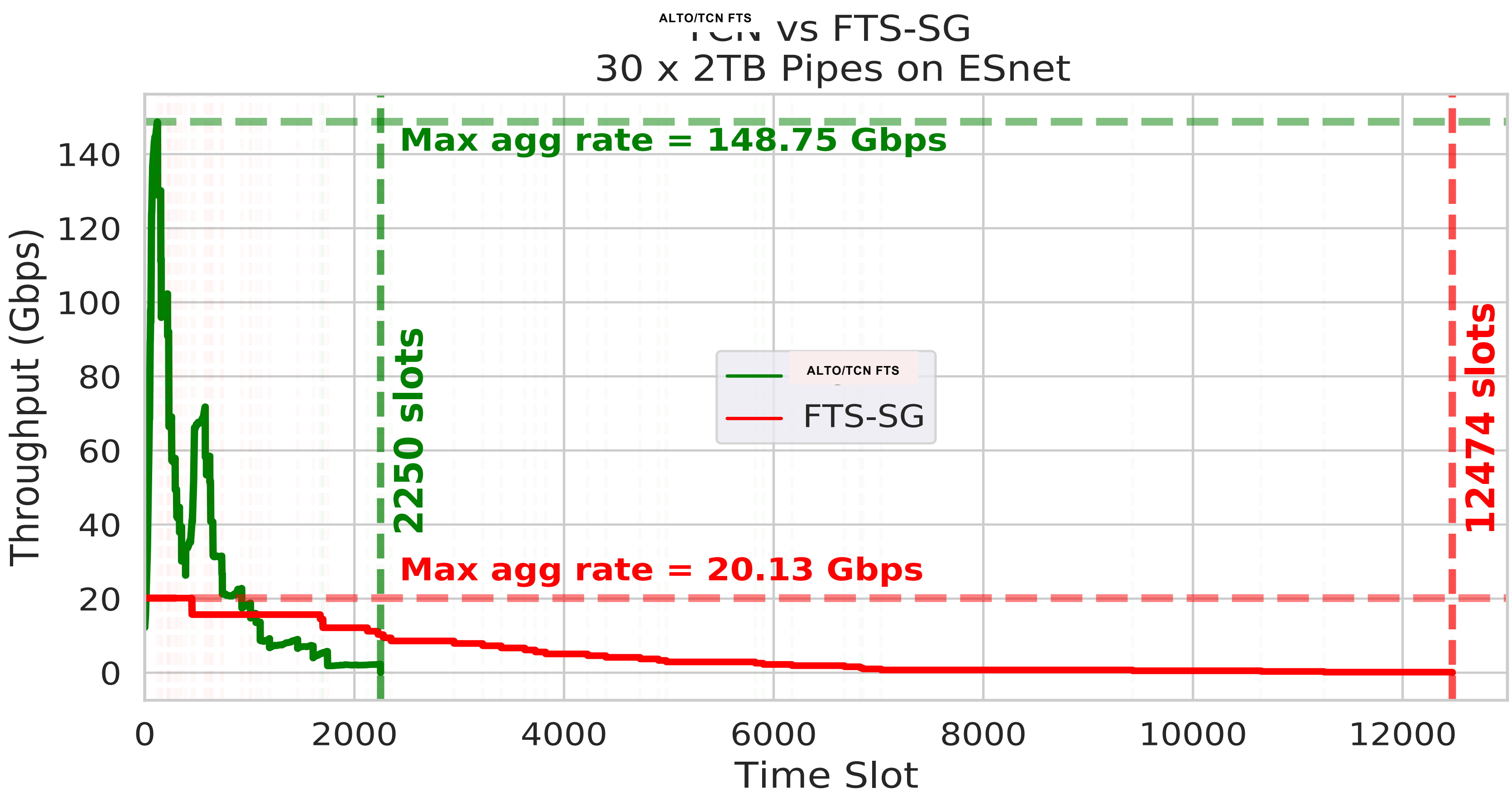
ALTO/FTS Control Details

- Integral, quadratic distance function
- Zero-order stochastic rounding

$$U(\tau) = \left(\sum_{i=1}^{K} w_i \tau_i\right) - \eta \cdot d(\tau, t \cdot K)^2$$

1. Basic Gradient	Gradient of control state n_i: $(\frac{\mathrm{d}a}{\mathrm{d}n_i})$	$\frac{\mathrm{d}a}{\mathrm{d}n_i} = \sum_{j=1}^{K} \frac{\mathrm{d}a}{\mathrm{d}T_j} \cdot \frac{\mathrm{d}T_j}{\mathrm{d}n_i}$
	1.1. $\frac{\mathrm{d}T_j}{\mathrm{d}n_i}$ is the gradient of the bottleneck	If $T_j(n) = \min(f_{j,1}(n), \ldots, f_{j,b}(n))$ and $k = \mathrm{argmin} f_{j,k}(n)$, then $\frac{\mathrm{d}T_j}{\mathrm{d}n_i} = \frac{\mathrm{d}f_{j,k}}{n_i}$
	1.2. Decide zero (implicit) or first order (w/ analytical expr)	$\frac{\mathrm{d}f_{j,k}}{\mathrm{d}n_i} = \begin{cases} \text{zero-ord est.} & \text{for blackbox } f_{j,k} \\ \text{first-ord grad.} & \text{otherwise.} \end{cases}$
	1.2a. Zero order estimate	$G(n, z) = \frac{f_{j,k}(n+z) - f_{j,k}(n)}{\|z\|^2} \cdot z$
	1.2b First order computation	Compute analytical expression: $\frac{\mathrm{d}f_{j,k}}{\mathrm{d}n_i}$
2. Momentum-Based Gradient Acceleration		Compute $g = (\frac{\mathrm{d}a(n)}{\mathrm{d}n_1}, \frac{\mathrm{d}a(n)}{\mathrm{d}n_2}, \ldots, \frac{\mathrm{d}a(n)}{\mathrm{d}n_K})$; Update $\mathbf{m} = (1-\alpha)\mathbf{m} + \alpha \cdot (\eta g)$; $n = cur.\mathbf{n} + int(\mathbf{m})$;
3. Discretize		$int(x) = \begin{cases} \lfloor x \rfloor & \text{with probability } 1 - (x - \lfloor x \rfloor) \\ \lfloor x \rfloor + 1 & \text{with probability } x - \lfloor x \rfloor. \end{cases}$

Basic ALTO/FTS Benchmarking ⇒ Real Topology (ESnet)

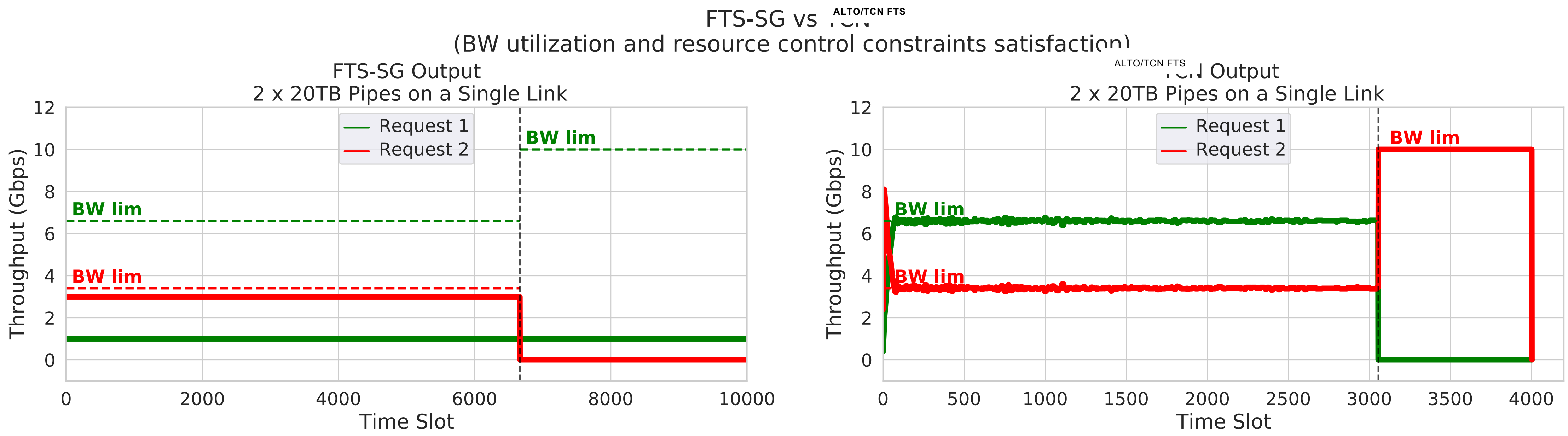


Setting: 30 <src, dst> pipes, one request per pipe, each request 20K transfers, file size = 100MB. the total in the workload is 60TB. Resource Control goal: all equal weights

1. **7.39x** total BW utilization.
2. **5.54x** Max RCT improvement. (Short-tailed)

Global Objective, Zero-order gradients, and Resource Control Constraints.

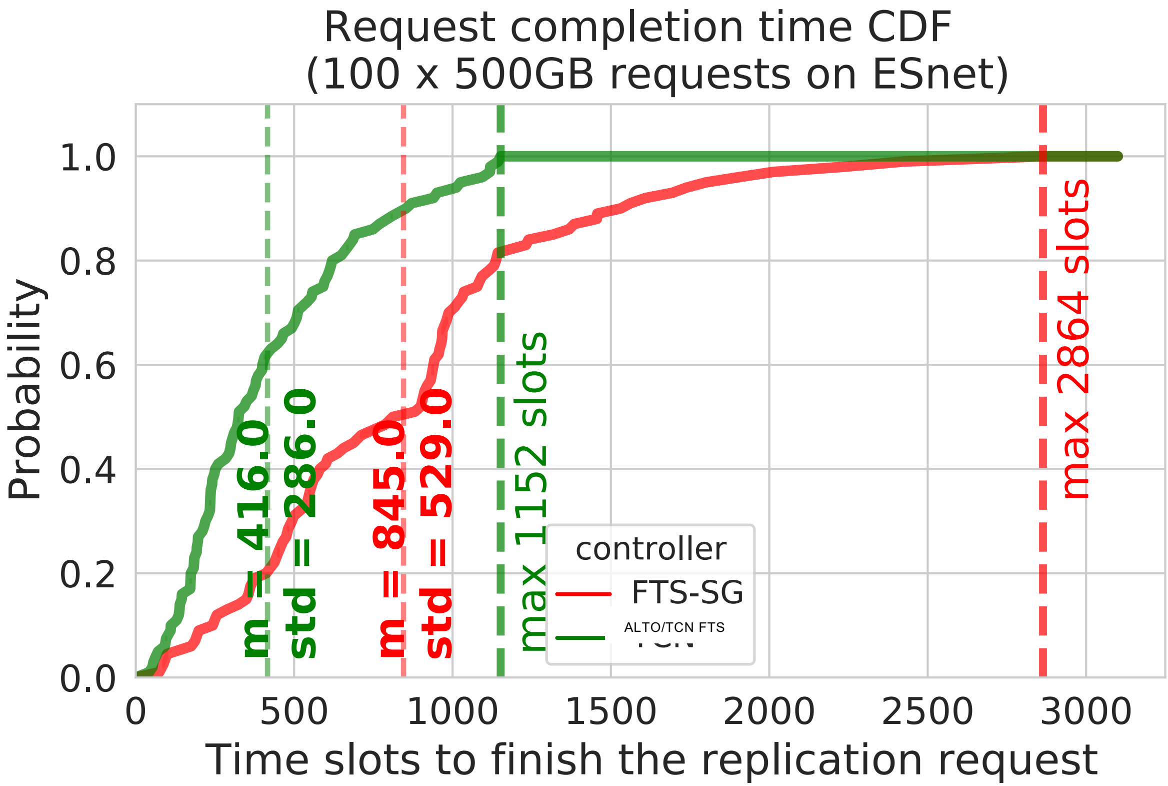
Basic Benchmarking: Results



	FTS Semi-Gradient (FTS-SG)	ALTO/TCN FTS
Total BW Utilization	Not optimal (6GB unused BW).	Fully utilized BW.
Resource Control	BW shares not satisfied.	BW allocated close to 2:1 spec.
RCT	Max RCT = 20,000 slots.	Max RCT = 4,000 slots.

FTS-SG depends on correct configuration (e.g., high enough default). **ALTO/TCN is fully automated**.

Request Performance Distribution

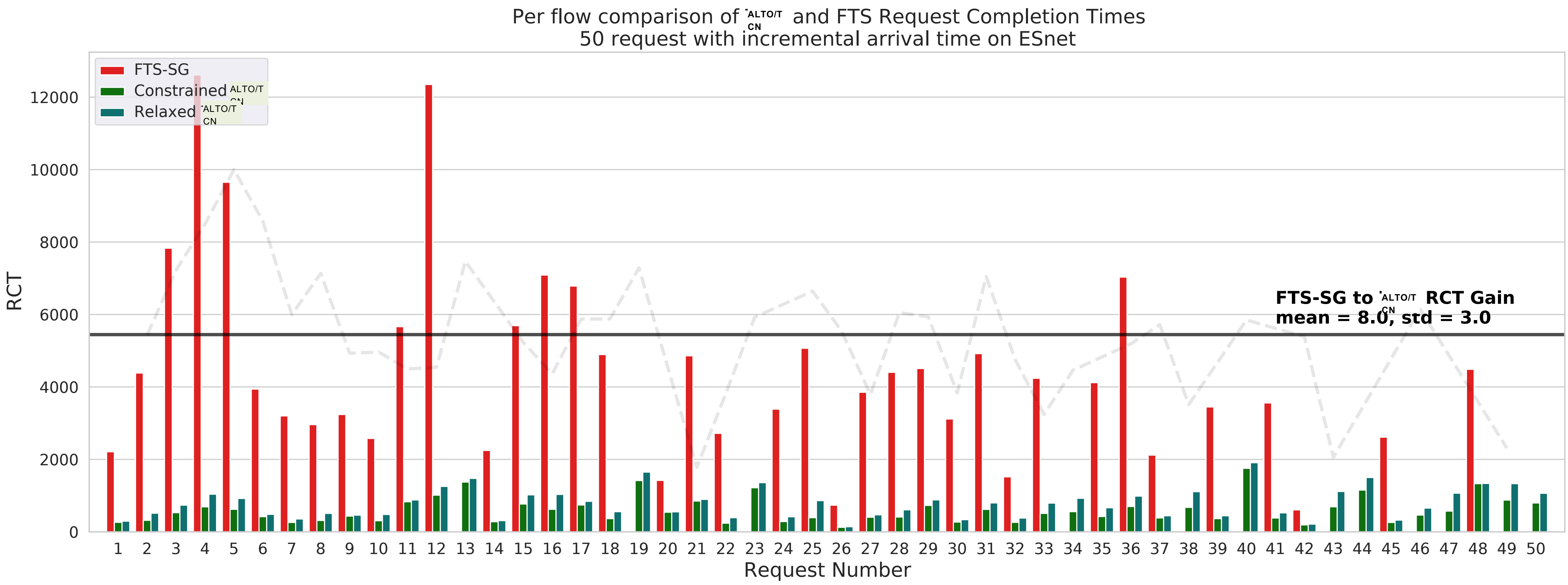


1. **2.03x** mean RCT improvement.
2. **2.49x** max RCT improvement.

Global Objective, Zero-order gradients, and Resource Control Constraints.

Setting: Similar to previous slide, but with modification to include more requests to show more details: 100 <src, dst> pipes, one request per pipe, each request 5K transfers, file size = 100MB.
Resource Control goal: all equal weights.

From All-Arrival Workload ⇒ Dynamic Arrival Workload

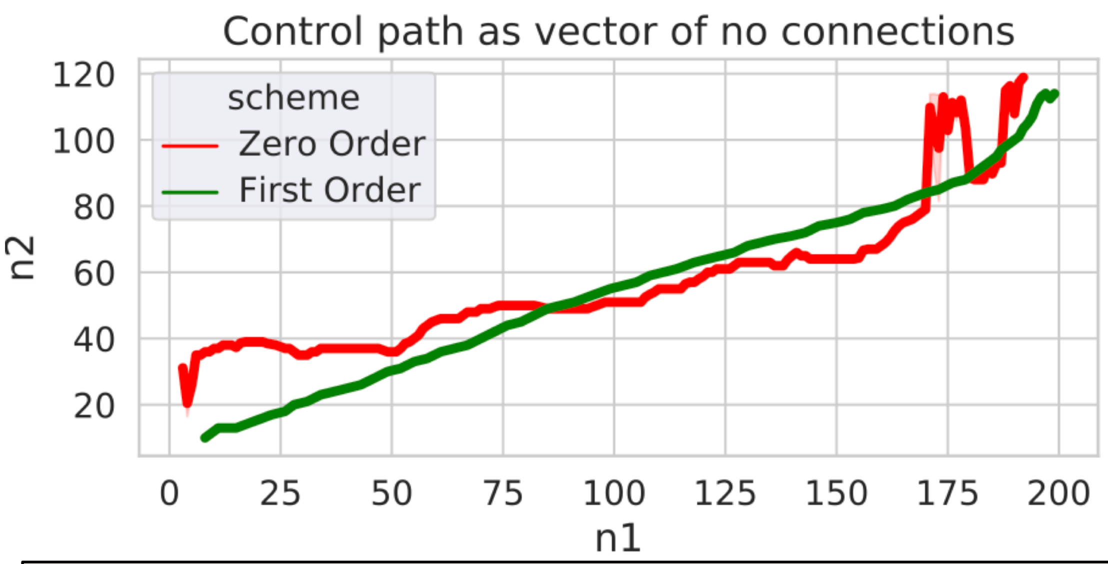


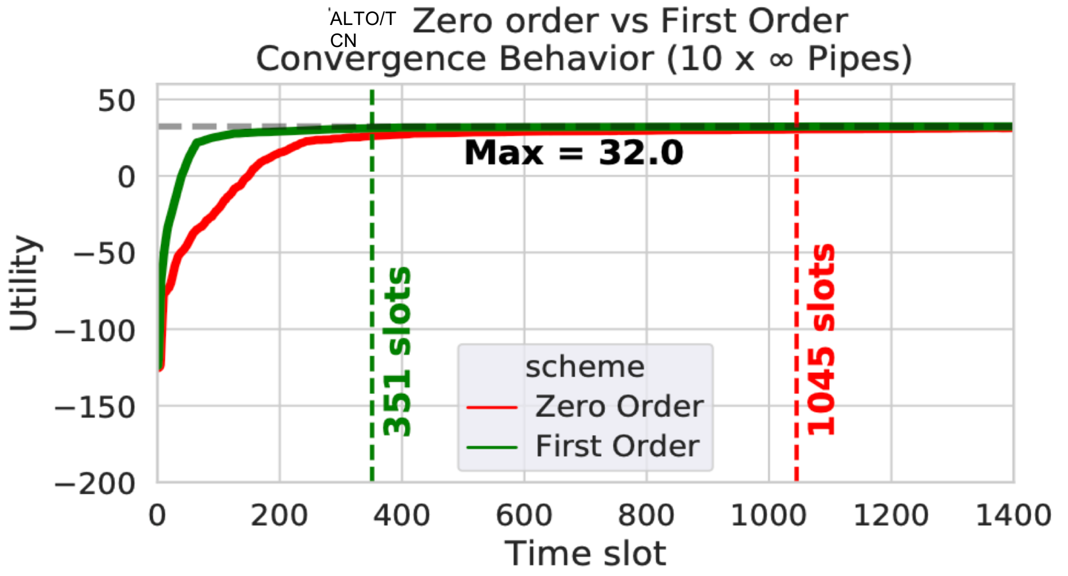
Setting: ESnet (67 nodes), selected 50 active pipes; each pipe has transfer workload arrives according to a arrival distribution (Poisson arrival, with parameter 1200 (every 200 time slot); Each replication request has N(40k, 20k) files, file size is 100MB.

8.0x improvement in RCT when using ALTO/TCN.

(Global Objective, Full Zero Order)

ALTO/TCN Zero-order vs First-order





2.97x improvement in convergence speed (# transient slots) with using first-order gradients.

First-order integrated ALTO/TCN vs Full Zero-order ALTO/TCN

Setting:ALTO/TCNology ESnet, selected 10 pipes, infinite backlog.

FTS Control Gap

Protocol 1 FTS Model Analyzed (Called for High Success Rate)

```
1: Define RL(x) = round(log_B(x))
2: procedure OPTIMIZEGOODSUCCESSRATE(state)
3:     if cur.ema < prev.ema then
4:         if RL(cur.ema) < RL(prev.ema) then
5:             decision = prevValue - decreaseStepSize
6:         else
7:             decision = prevValue
8:         end if
9:     else if cur.ema > prev.ema then
10:        decision = prevValue + increaseStepSize
11:    else                                        ▷ emas are equal
12:        decision = prevValue + increaseStepSize
13:    end if
14: end procedure
```

A Semi Zero-Order Gradient Alg Optimizing for Each Pipe

Keep track of the exponential moving average (EMA) of throughput.

$$E_i(t+1) = \alpha T_i(t+1) + (1-\alpha)E_i(t)$$

Update the number of connections based on EMA.

$$n_i(t+1) = \begin{cases} n_i(t) - 1 & RL_B(E_i(t+1)) < RL_B(E_i(t));\ \text{Line 4} \\ n_i(t) + 1 & E_i(t+1) \geq E_i(t);\ \text{Lines 9,11} \\ n_i(t) & \text{else} \end{cases}$$

resource flexibility/fairness control gap

THEOREM 4.2 (CONSERVATION THEOREM). *Let $K = \max \frac{M_i}{m_i}$. Then as long as $B > (1 - \alpha + \alpha K^2)$, the quantity*

$$V_t(t) = n_i(t) - \text{round}(\log_B(E_i(t))$$

only ever stays constant or increases.

efficiency gap

Theorem: In a **Throughput-Deterioration Model, semi zero order** will achieve throughput that is **<=** 1/√B of the **optimal** (under default settings).