RaQSaC: RaptorQ-based data transport for low earth orbit Satellite Constellations

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Introduction

- Currently over 1800 Low-Earth Orbit (LEO) satellites orbiting the earth which are all part of SpaceX's vast plan for global high-speed internet access.

- Features Include:
  - Interconnected dynamic mesh of thousands of satellites
  - Substantial Latency reductions in comparison to the best fibre available today
  - Aggregate capacity expected to reach multiple Tbps
  - Average Round-Trip-Time (RTT) in a sub-10ms range between a the first satellite and Earth.

SpaceX Current Authorization					
Orbital Planes	72	72	36	6	4
Satellites per plane	22	22	20	58	43
Altitude	550 km	540 km	570 km	560 km	560 km
Inclination	53°	53.2°	70°	97.6°	97.6°

Project Goal

- Take an exploratory approach to devising data transport protocols with appropriate congestion control algorithms for LEO satellite constellations

  - Understand the latency characteristics of LEO constellations along with the potential of inter-packet latency variation.

  - Explore design characteristics of a novel receiver-driven data transport, driven by our observations.

LEO Satellite Constellation Simulation Framework

We developed a LEO satellite simulation framework, allowing us to model existing and future satellite network constellations

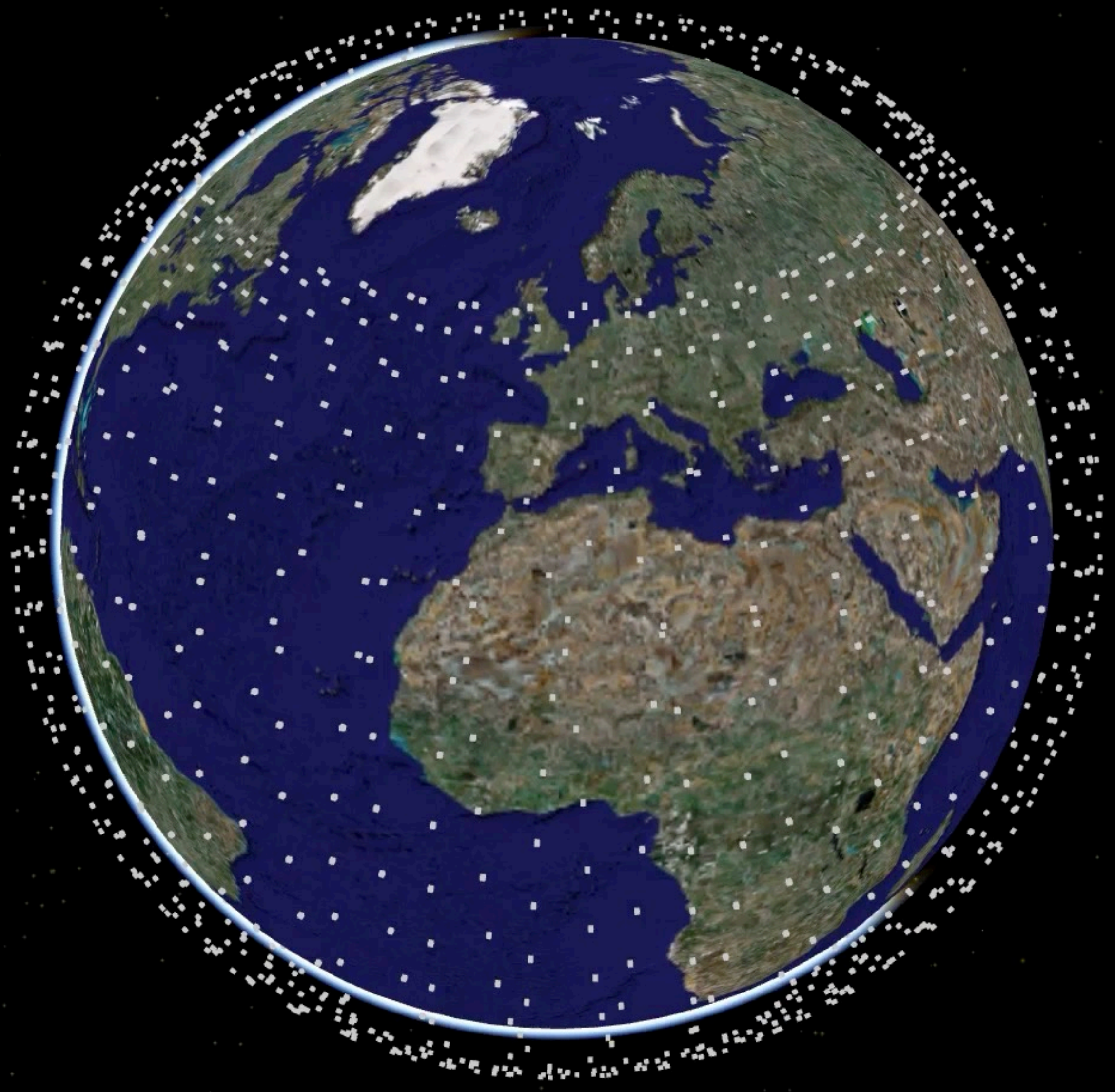
- Implemented within the OMNeT++ simulation library and framework

<u>Purpose</u>

- Drive the design exploration
- To test our protocol on realistic satellite network deployments

OMNeT++ Community Summit 2021 Paper: https://summit.omnetpp.org/2021/assets/pdf/OMNeT_2021_paper_6.pdf

LEO Satellite Constellation Framework: https://github.com/Avian688/leosatellites



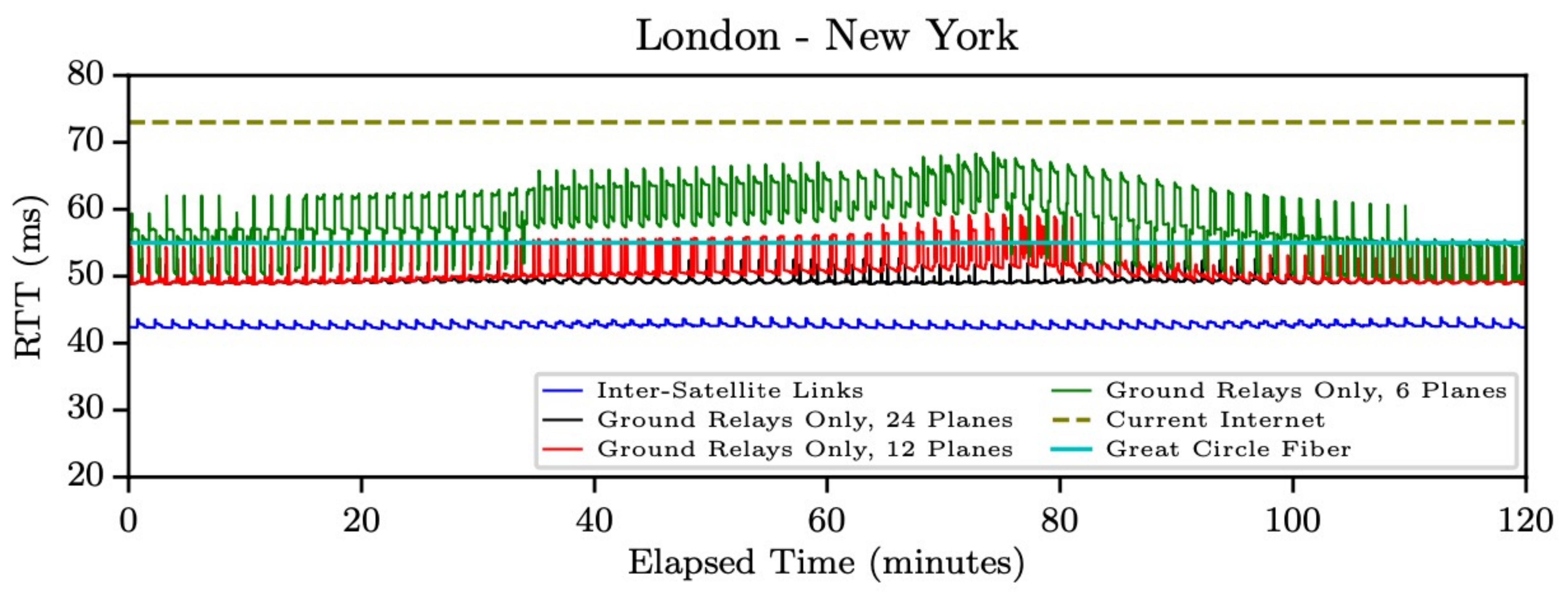
Experimentation

To understand fully the characteristics of these networks, we did thorough experimentation using the simulation model.

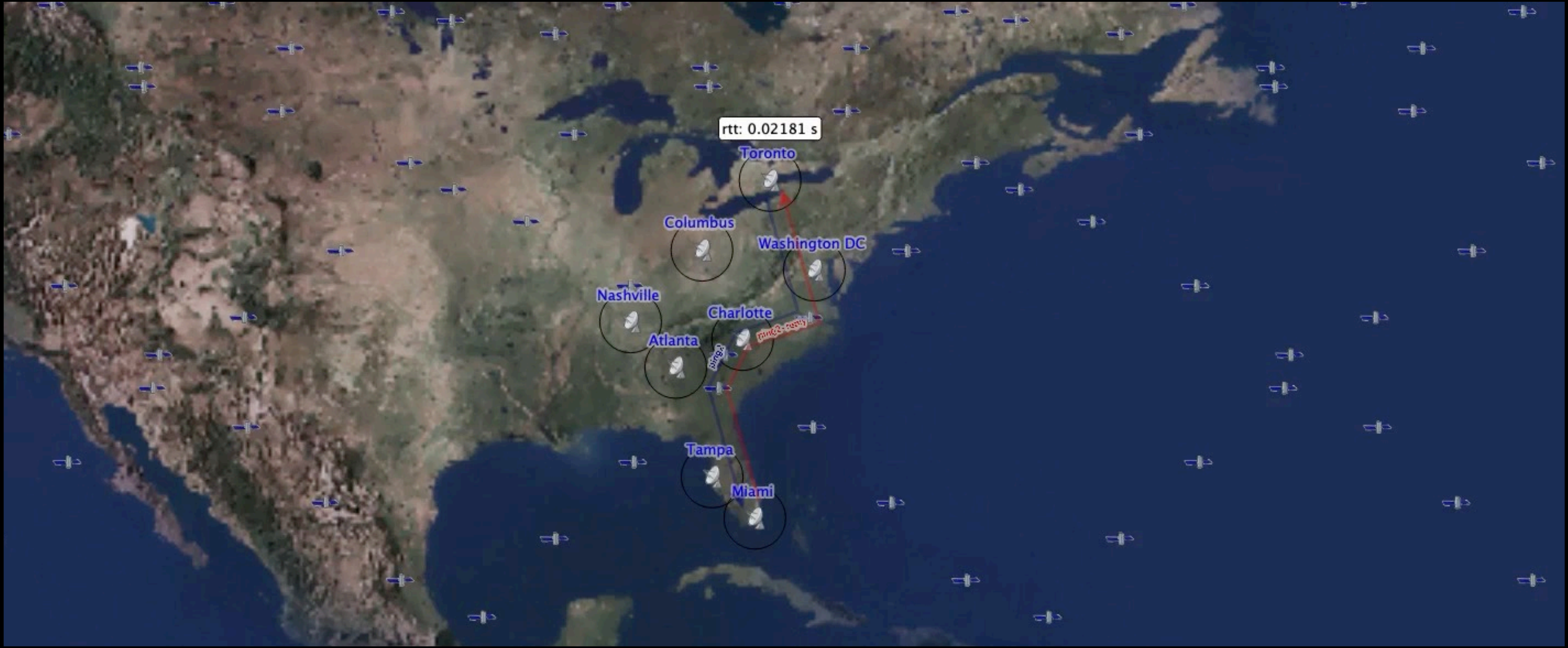
Initial focuses:

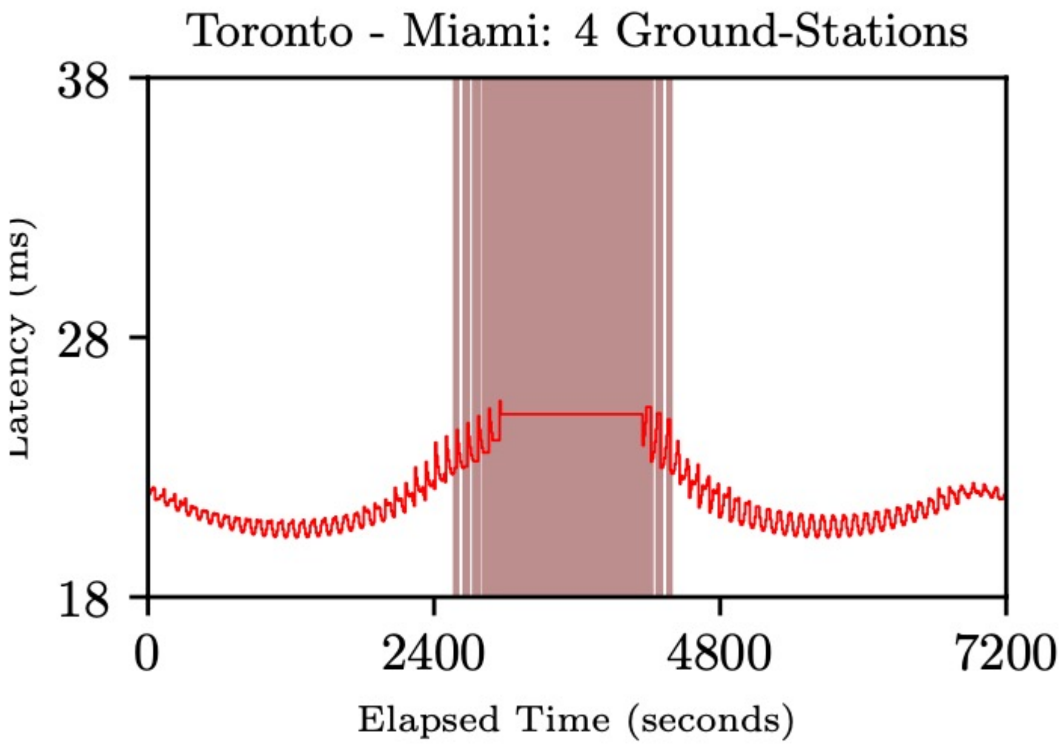
- Latency Variation
- Inter-packet Latency (Jitter)

London – New York

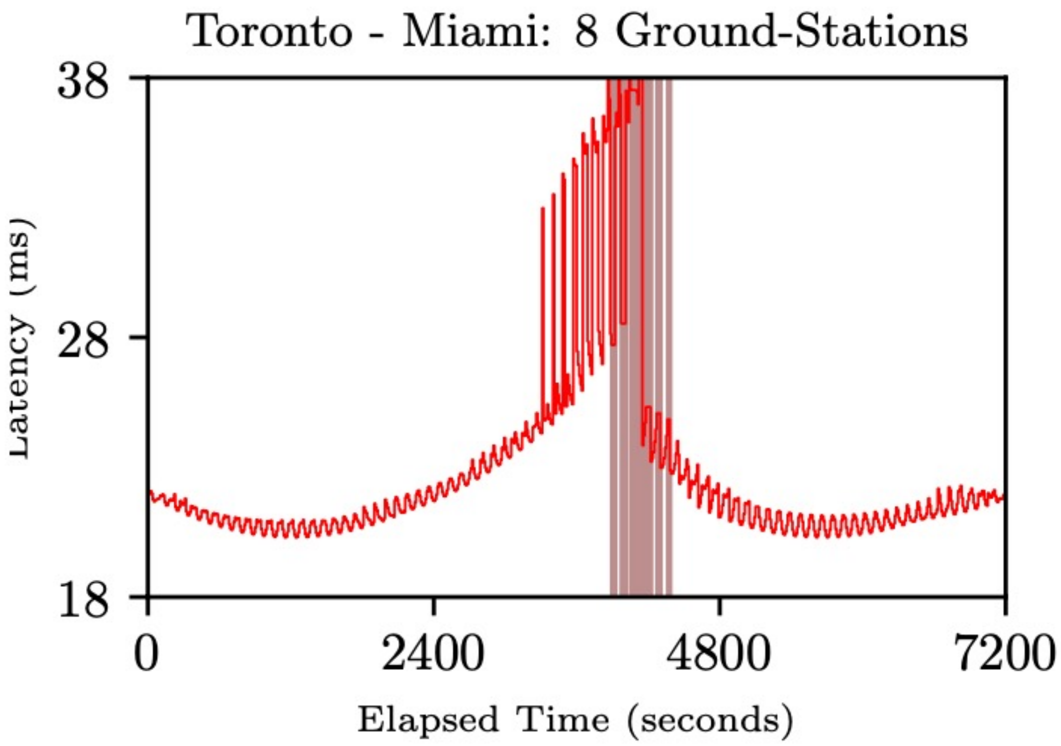

London - New York
RTT (ms)
Elapsed Time (minutes)
80
70
60
50
40
30
20
0
20
40
60
80
100
120
Inter-Satellite Links
Ground Relays Only, 24 Planes
Ground Relays Only, 12 Planes
Ground Relays Only, 6 Planes
Current Internet
Great Circle Fiber

Toronto – Miami

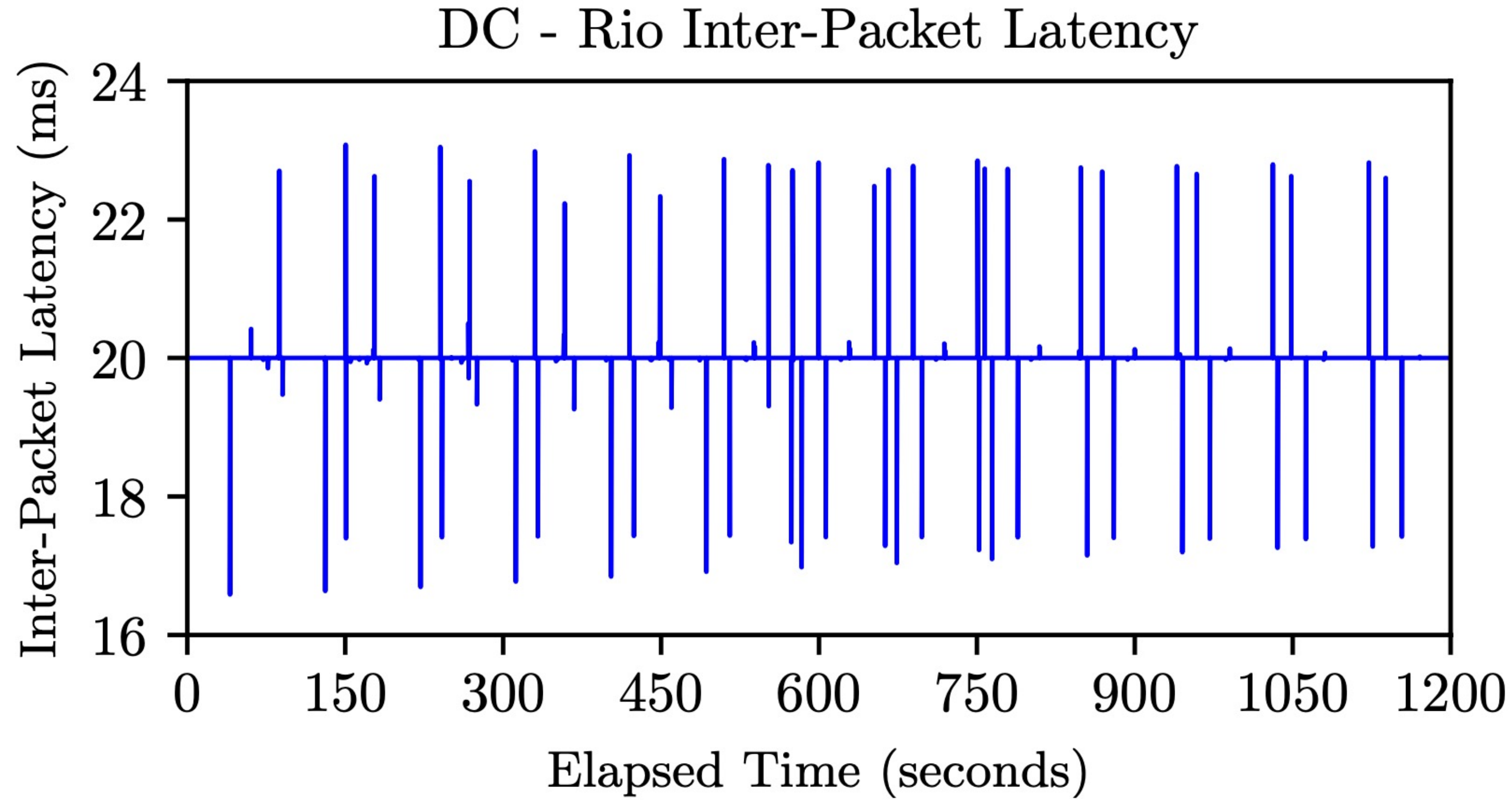




(a) 4 Ground-Stations



(b) 8 Ground-Stations


DC - Rio Inter-Packet Latency
Inter-Packet Latency (ms)
24
22
20
18
16
0
150
300
450
600
750
900
1050
1200
Elapsed Time (seconds)

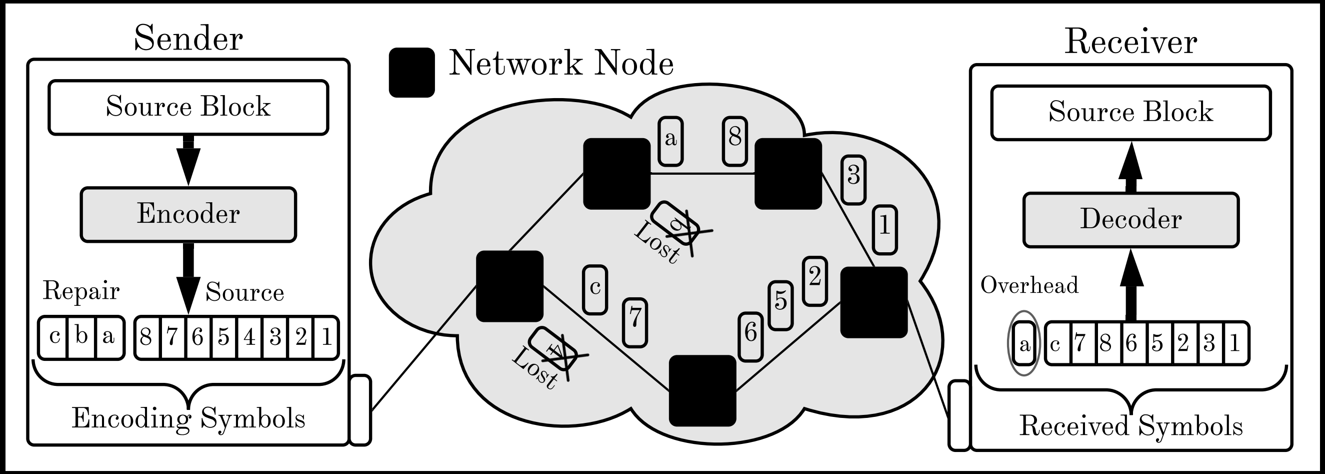
Challenges

- Latency Variation
- Multiple paths that change over time.
- Fluctuating bandwidth.
- Hotspots

RaptorQ

We integrate RaptorQ coding into the core of data transport

- Systematic Code
- Spray symbols (not per-flow)
- Code is rateless (endless supply)
- Ordering is not important
- Zero retransmissions



How does RaptorQ address the challenges?

- Latency Variation – Immune to reordering
- Multiple paths that change over time – Source and Repair symbols can be sprayed across all paths.
- Fluctuating bandwidth – Losses are less important due to no need to retransmit a lost symbol.

Receiver – Driven Approach

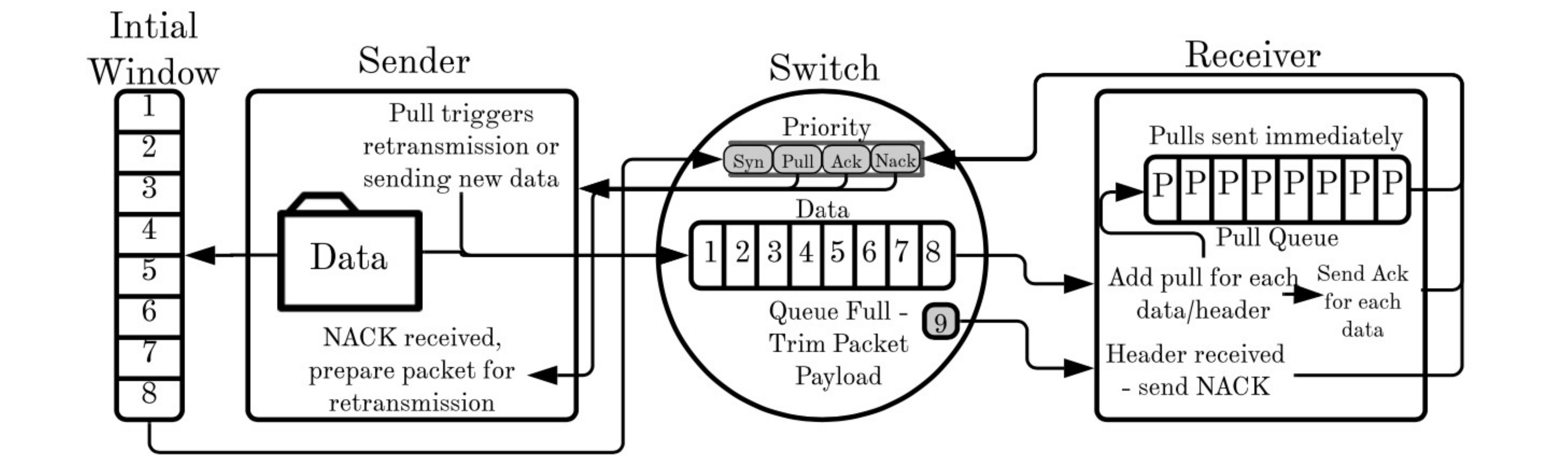
Receivers manage the rate of data being sent to them by senders.

We draw inspiration from datacentre data transport protocols [1, 2]

- Packet spraying
- Pull-based data transport with packet trimming.

[1] *Handley et al. Re-architecting datacenter networks and stacks for low latency and high performance. SIGCOMM '17.*

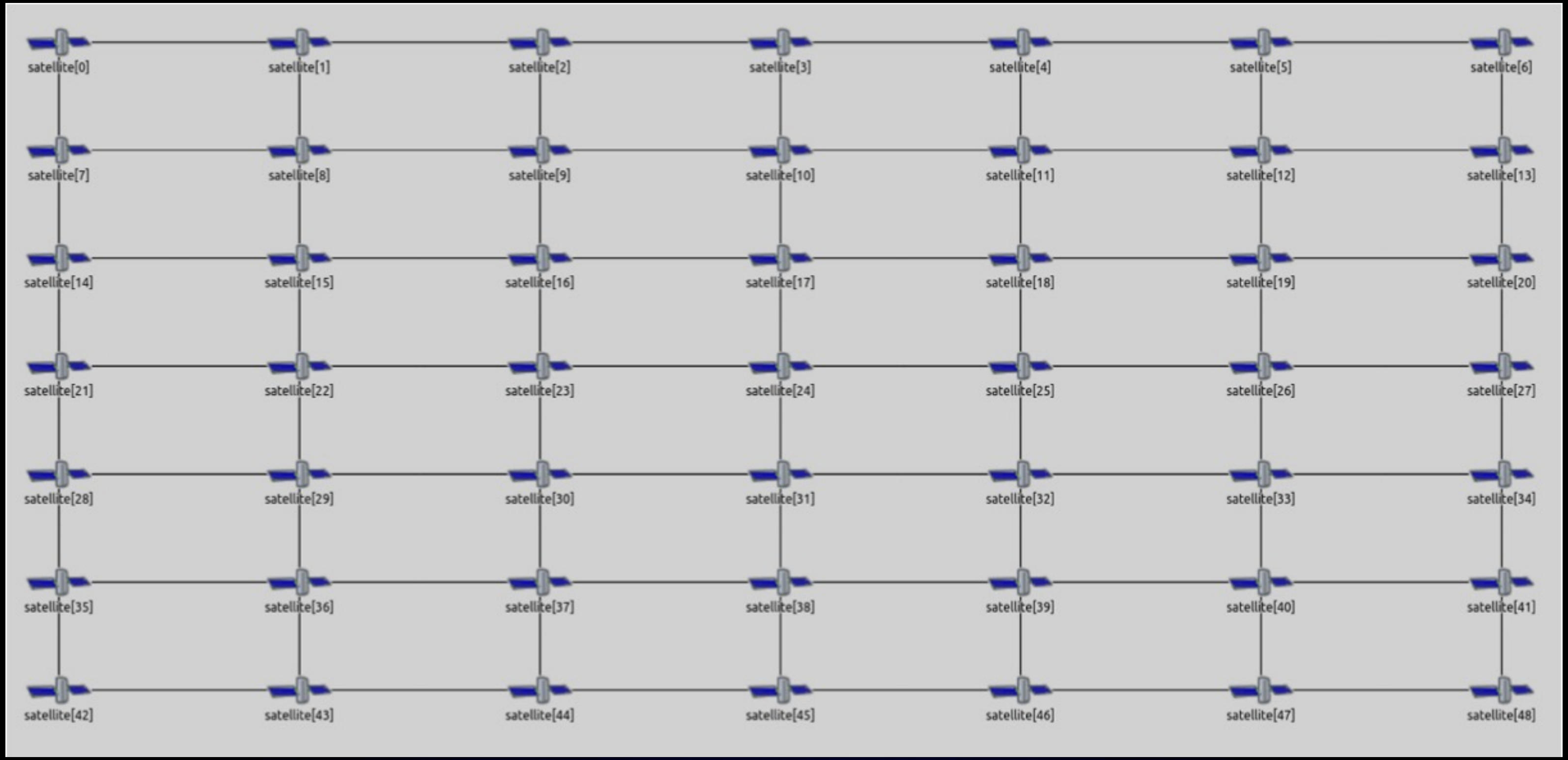
[2] *Montazeri et al. Homa: a receiver-driven low-latency transport protocol using network priorities. SIGCOMM '18.*

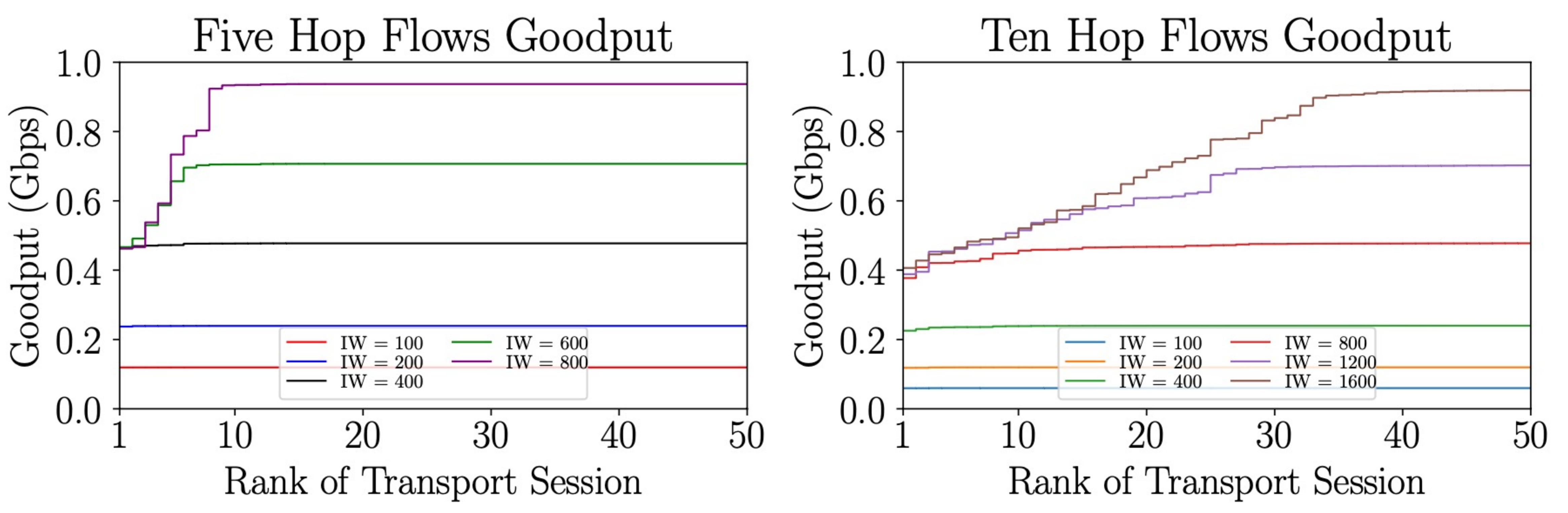


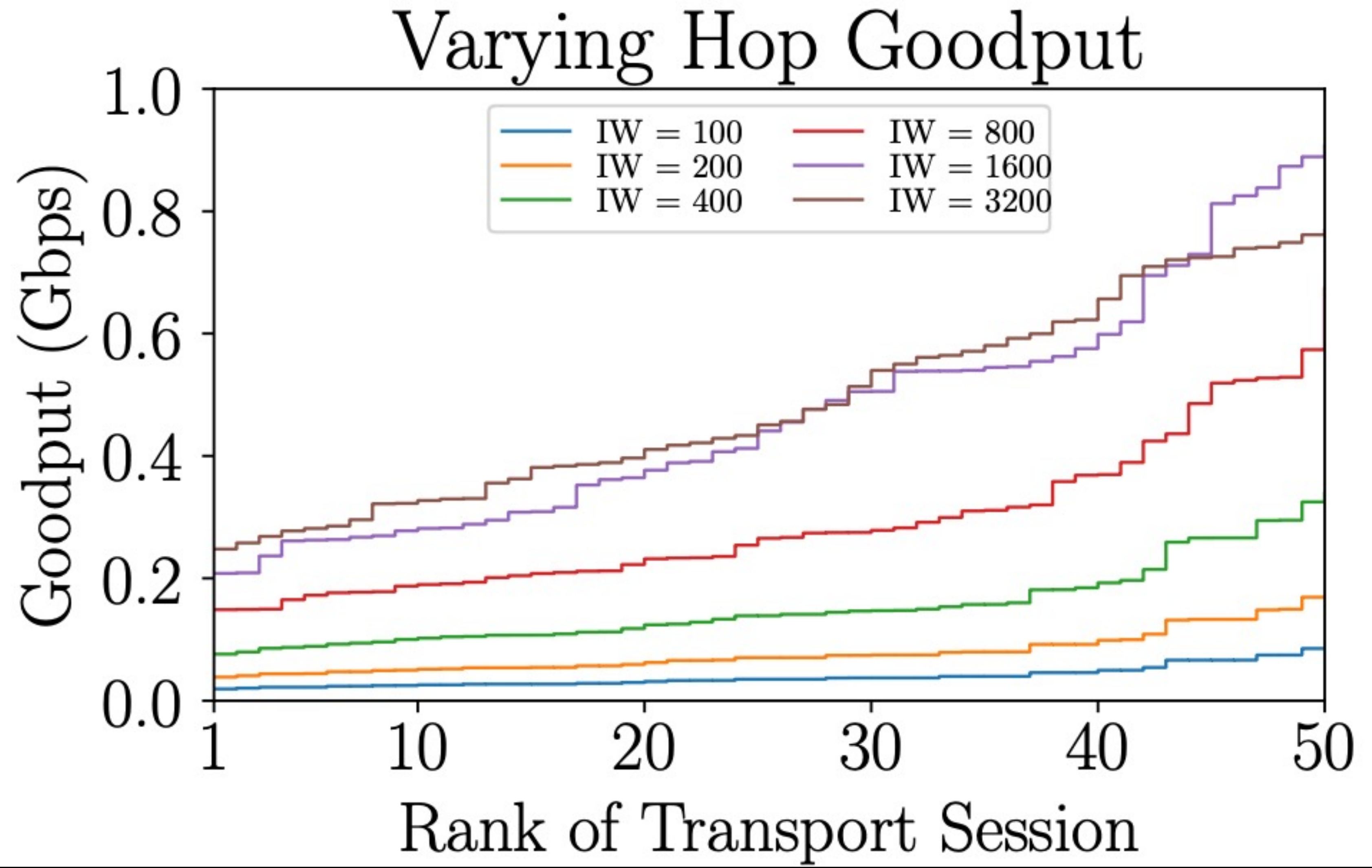
Intial Window
1
2
3
4
5
6
7
8
Sender
Pull triggers retransmission or sending new data
Data
NACK received, prepare packet for retransmission
Switch
Priority
Syn
Pull
Ack
Nack
Data
1 2 3 4 5 6 7 8
Queue Full - Trim Packet Payload
9
Receiver
Pulls sent immediately
P P P P P P P P
Pull Queue
Add pull for each data/header
Send Ack for each data
Header received - send NACK

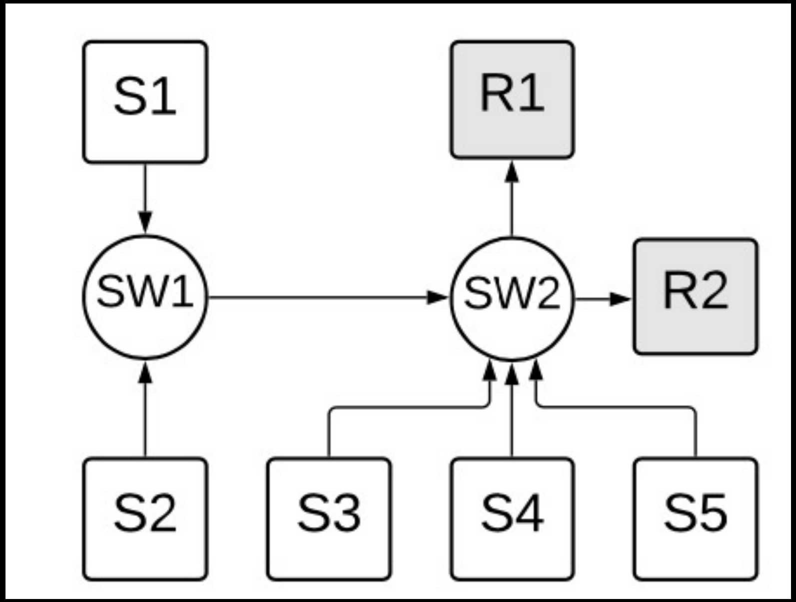
Receiver-Driven Approach Experiments

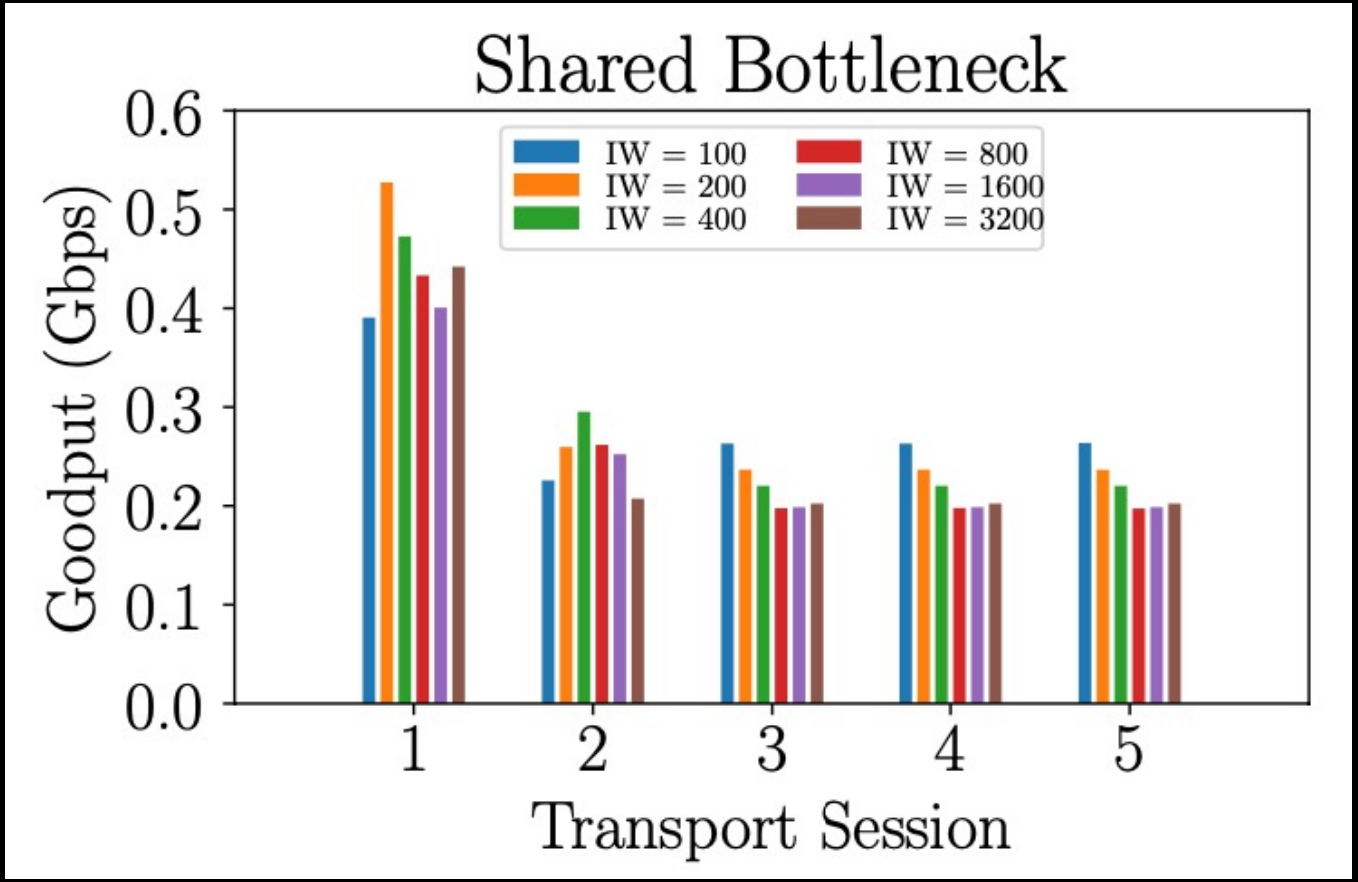
- Manhattan Topology




Five Hop Flows Goodput
Goodput (Gbps)
Rank of Transport Session
IW = 100
IW = 200
IW = 400
IW = 600
IW = 800
Ten Hop Flows Goodput
Goodput (Gbps)
Rank of Transport Session
IW = 100
IW = 200
IW = 400
IW = 800
IW = 1200
IW = 1600


Varying Hop Goodput
Goodput (Gbps)
1.0
0.8
0.6
0.4
0.2
0.0
1
10
20
30
40
50
Rank of Transport Session
IW = 100
IW = 200
IW = 400
IW = 800
IW = 1600
IW = 3200


S1
R1
SW1
SW2
R2
S2
S3
S4
S5


Shared Bottleneck
Goodput (Gbps)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
IW = 100
IW = 200
IW = 400
IW = 800
IW = 1600
IW = 3200
1
2
3
4
5
Transport Session

Challenges

Latency Variation – Delay-Based congestion control algorithms will constantly adjust the sending rate, causing severe under-utilisation or congestion. Motivates the need of a non-delay congestion control.

Multiple paths that change over time – End-to-end shortest paths change every few seconds.

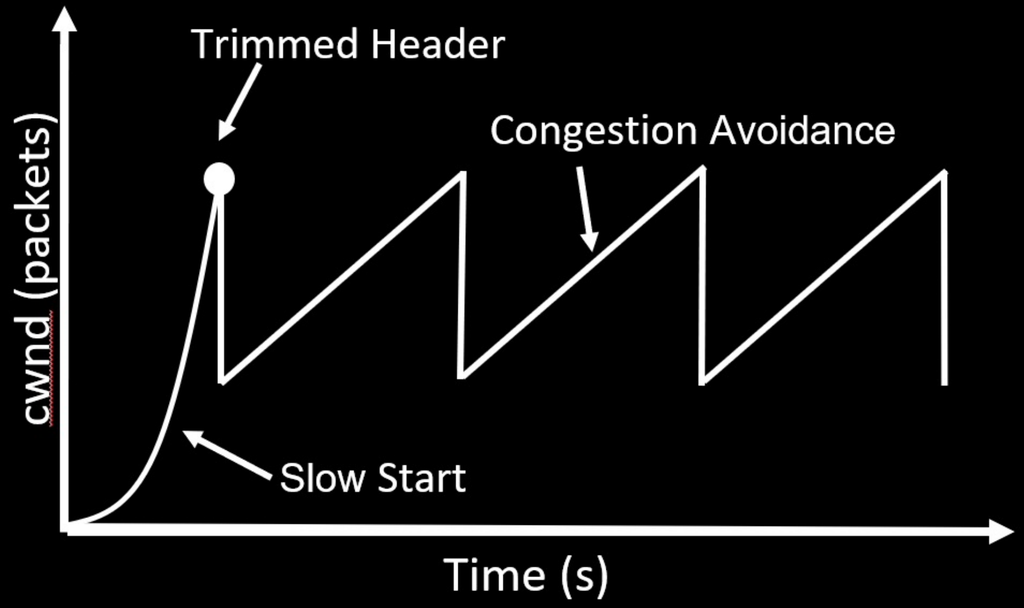
Hotspots – Shortest-path routing on mesh networks is susceptible to creating hotspots. Packet spraying and pull-based data transport can easily accommodate alternate routing strategies (such as *k-shortest-path*)

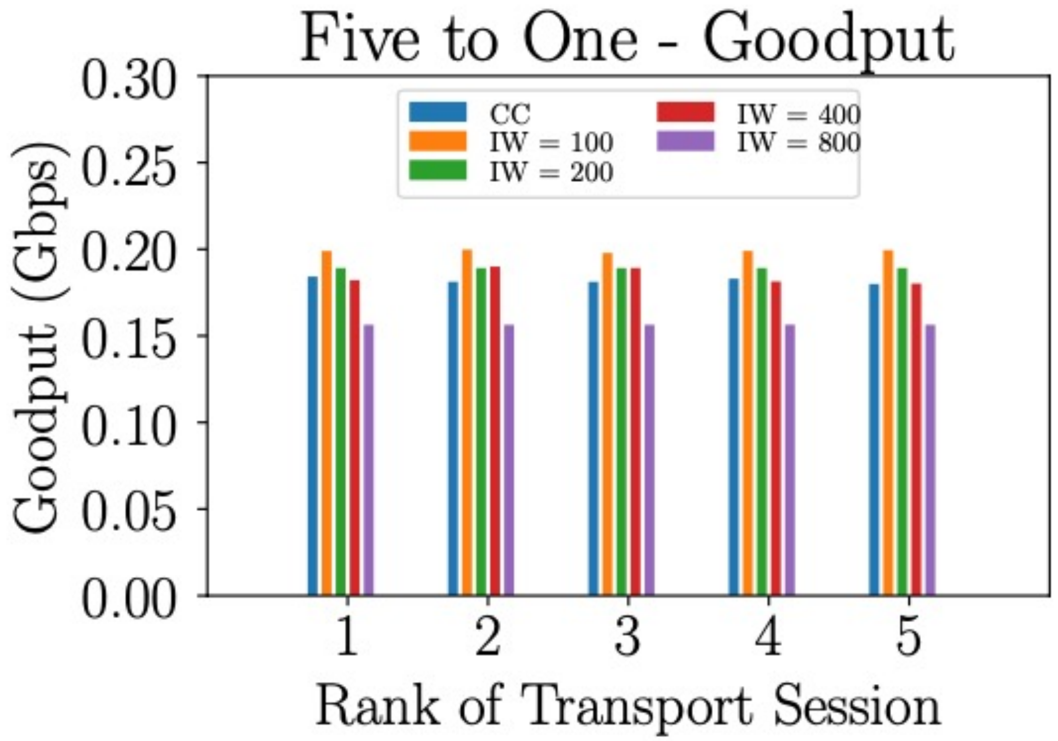
Congestion Control

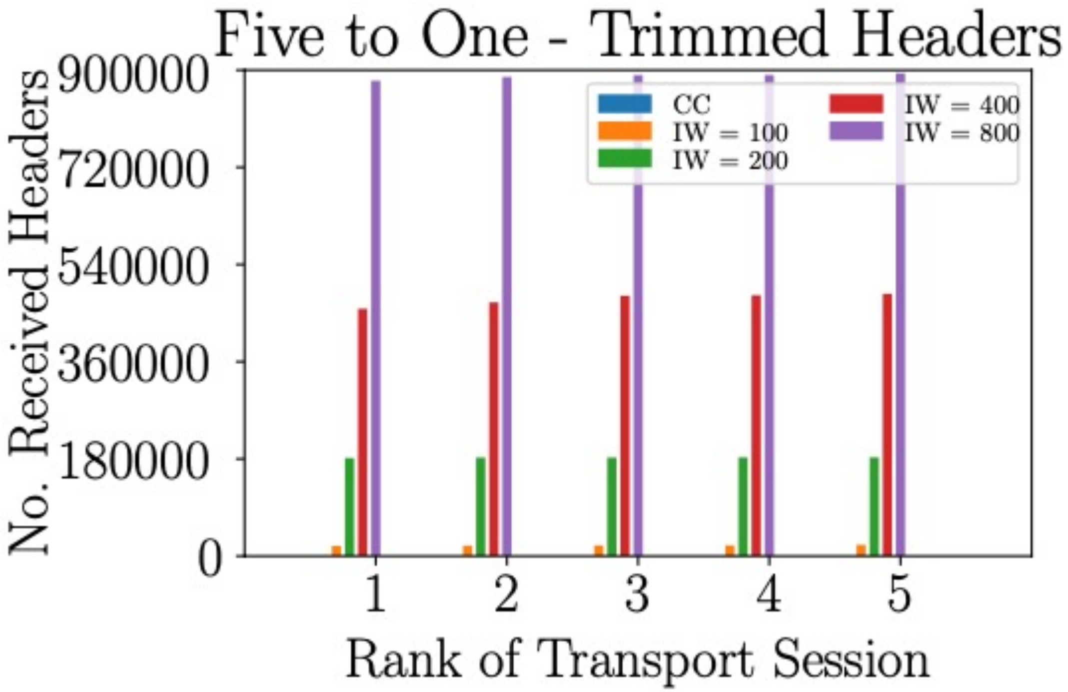
We implemented an additive-increase multiplicative decrease (AIMD) scheme on top of the receiver-driven approach.

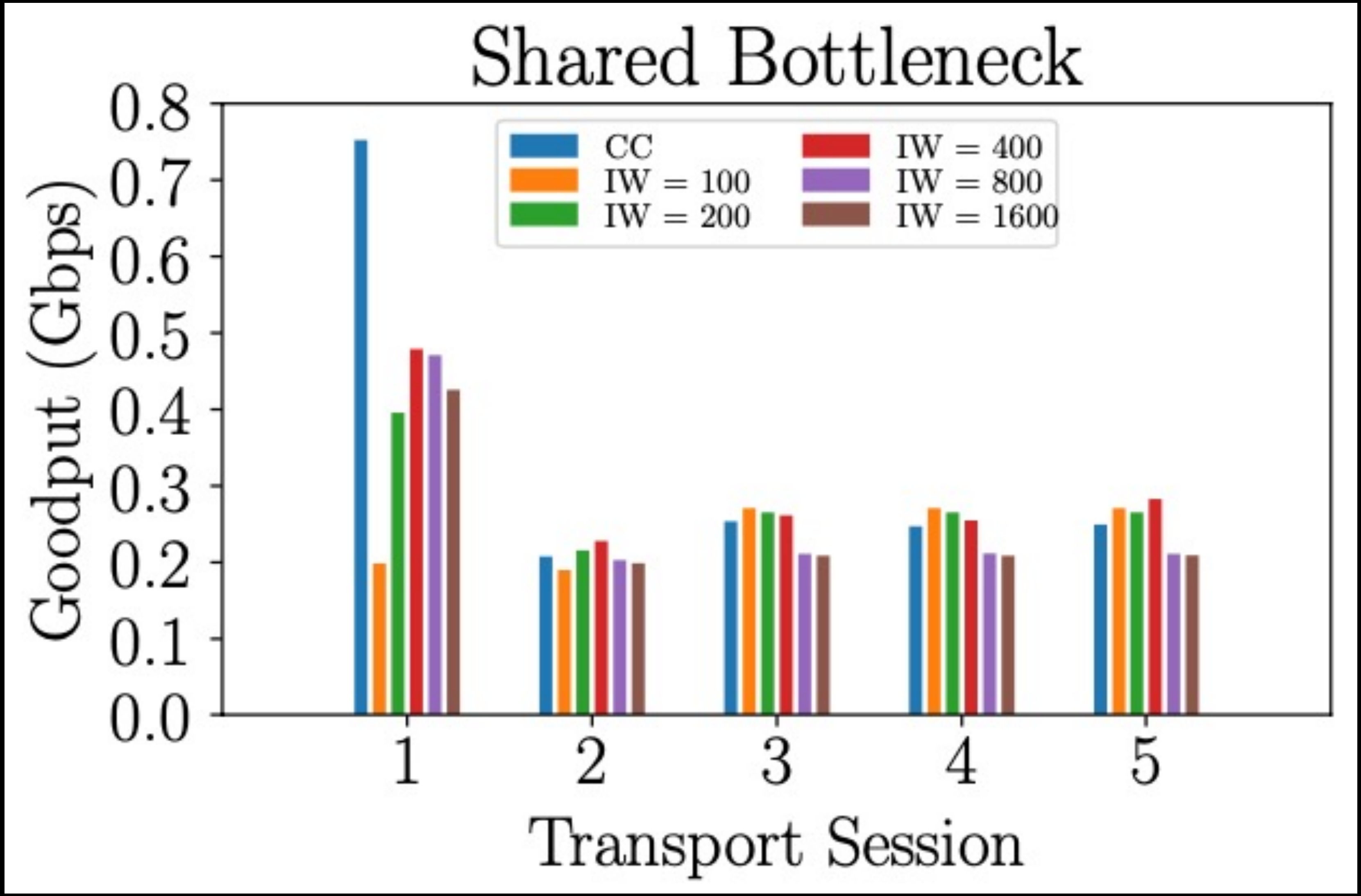
- Slow Start Phase
- Congestion Avoidance phase

We use trimmed headers to infer that there is congestion in the network!




Five to One - Goodput
Goodput (Gbps)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
CC
IW = 100
IW = 200
IW = 400
IW = 800
1
2
3
4
5
Rank of Transport Session


Five to One - Trimmed Headers
No. Received Headers
900000
720000
540000
360000
180000
0
CC
IW = 100
IW = 200
IW = 400
IW = 800
1
2
3
4
5
Rank of Transport Session


Shared Bottleneck
Goodput (Gbps)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
CC
IW = 100
IW = 200
IW = 400
IW = 800
IW = 1600
1
2
3
4
5
Transport Session

Current Work

- We are evaluating the receiver-driven approach with congestion control further, including testing the protocol on large-scale moving satellites constellations.
- We are also evaluate one-to-many and many-to-one modes of the RaptorQ receiver-driven data transport.
- Lastly, we are evaluating alternate routing approaches, e.g. *k-shortest-path*