Computer Networks Project

Github repo link

Group Members :
Adarsh Dhakar :22cs01040
Avik Sarkar :22cs01060
Debargha Nath :22cs01070
Soham Chakraborty :22cs02002

Network Simulator Used: ns3

Concept used:

1. Congestion Metric (CM)

We define a **Congestion Metric (CM)** to evaluate the performance of a network topology or congestion control algorithm, incorporating key Quality of Service (QoS) parameters. The metric combines the impact of latency, throughput, and jitter to provide a comprehensive assessment of network congestion.

Parameters Considered:

1. **Delay (D)** – The average end-to-end packet delay.
2. **Throughput (T)** – The total amount of successfully delivered data per unit time.
3. **Jitter (J)** – The variation in packet delay, indicating delivery smoothness.

Metric Formula:

$CM=\alpha \cdot D - \beta.T + \gamma \cdot J$
Where:

- α, β, and γ are tunable weighting coefficients that reflect the relative importance of delay, throughput, and jitter respectively.
- All parameters are normalized based on predefined scale factors to ensure equal weightage of both.

Cases for measurements:

	α	β	γ
delay	1	0	0
delay, throughput	1/2	1/2	0
delay, jitter	3/4	1/4	0
delay, throughput, jitter	2/5	2/5	1/5

2. Topologies used for Experimentation

To evaluate the performance of congestion control algorithms under varying network structures, we utilize the following standard topologies. Each topology consists of **10 nodes**, ensuring consistency in comparison:

- **Linear**
- **Mesh**
- **Ring**
- **Star**

3. Objective: Minimization of the Congestion Metric

To enhance overall network performance, our primary goal is to **reduce the Congestion Metric (CM)**, which is a function of key network parameters such as **delay**, **throughput**, and **jitter**. To achieve this, we introduce an adaptive strategy that dynamically adjusts the **congestion window (`cwnd`)**. The change in congestion window is governed by the following equation:

Δcwnd =

$$(\mathbf{1} - \boldsymbol{PL}) \times \frac{\boldsymbol{a}}{\boldsymbol{b}+\boldsymbol{cwnd}} + \boldsymbol{PL} \times (\boldsymbol{c} \times \boldsymbol{cwnd} - \boldsymbol{d})$$

- **Δcwnd** The incremental change to the congestion window.
- **PL** – Takes Boolean values only 0 and 1, when a packet loss occurs via 3-ACKs and drops the value of cwnd.
- **a,b –** Controls **Congestion window increase**, which very closely resembles Additive Increase with a varied slope and some intercept.
- **c,d –** Controls **Congestion window decrease**, which very closely resembles Multiplicative Decrease with a varied drop ratio and intercept.
- **Cwnd -** The current congestion-window size (in or segments).

Vales of a,b,c,d to resemble standard algorithms:

*** Tahoe: a = 1, b = 0, c = 1, d = 1**

$$\Delta\text{cwnd} = \frac{\mathbf{1}}{\boldsymbol{cwnd}} - \boldsymbol{PL} \times (\frac{\mathbf{1}}{\boldsymbol{cwnd}} + \boldsymbol{cwnd} - \mathbf{1})$$

*** Reno: a = 1, b = 0, c = 1/2, d = 0**

$$\Delta\text{cwnd} = \frac{\mathbf{1}}{\boldsymbol{cwnd}} - \boldsymbol{PL} \times (\frac{\mathbf{1}}{\boldsymbol{cwnd}} + \frac{\boldsymbol{cwnd}}{\mathbf{2}})$$

4. Gradient-Descent-Driven Parameter Tuning

After each measurement interval (20 seconds in the code):

1. **Compute** the current Congestion Metric,
   $CM = \alpha.D - \beta.T + \gamma.J$

2. **Estimate** each partial derivative via finite differences for each parameter a,b,c,d

   E.g: $\partial CM/\partial x \approx (CM(x+\varepsilon) - CM(x)) / \varepsilon$

3. **Update** parameters along the negative gradient:
   $a \leftarrow a - \alpha * \partial CM/\partial a$,
   $b \leftarrow b - \alpha * \partial CM/\partial b$,
   $c \leftarrow c - \alpha * \partial CM/\partial c$,
   $d \leftarrow d - \alpha * \partial CM/\partial d$,
   where α is the learning rate.

- **Convergence & Termination**
  Iterate until the relative change in CM falls below a preset threshold, indicating that { {a,b,c,d} has converged to a near-optimal operating point.

This procedure unifies **online congestion control** (via **Δcwnd) with offline optimization (via gradient descent), systematically driving the network toward a minimal congestion metric.**

5. Screenshots for Topology behaviour of Congestion Metric using Gradient Descent:

Linear Topology:

```
debar@MacBook-Air cmake-cache % cmake --build . --target scratch_Final_Linear
[  0%] Building CXX object scratch/CMakeFiles/scratch_Final_Linear.dir/Final_Linear.cc.o
[  0%] Linking CXX executable /Users/debar/ns-3-allinone/ns-3-dev/build/scratch/ns3-dev-Final_Linear-default
debar@MacBook-Air cmake-cache % /Users/debar/ns-3-allinone/ns-3-dev/build/scratch/ns3-dev-Final_Linear-default


 ---- START ----

0 ->  a: 1.000000, b: 0.000000, c: 0.500000, d: 0.000000, Throughput: 2.384400, Jitter: 0.003145, CM: -0.380230
1 ->  a: 1.000000, b: 0.000000, c: 0.500000, d: 0.000000, Throughput: 2.384400, Jitter: 0.005153, CM: -1.384117
2 ->  a: 1.134316, b: -0.046385, c: 0.001000, d: -0.059048, Throughput: 2.494816, Jitter: 0.006381, CM: -1.943070
3 ->  a: 1.272154, b: -0.058086, c: 0.001000, d: -0.064278, Throughput: 2.608984, Jitter: 0.006459, CM: -1.924814
4 ->  a: 1.305611, b: -0.068297, c: 0.001814, d: -0.063288, Throughput: 2.638464, Jitter: 0.006415, CM: -1.888492
5 ->  a: 1.313182, b: -0.078380, c: 0.003927, d: -0.062205, Throughput: 2.652936, Jitter: 0.006375, CM: -1.861155
6 ->  a: 1.312447, b: -0.088766, c: 0.005128, d: -0.061346, Throughput: 2.649720, Jitter: 0.006345, CM: -1.847595
7 ->  a: 1.312645, b: -0.099098, c: 0.004210, d: -0.060886, Throughput: 2.652936, Jitter: 0.006325, CM: -1.836014
8 ->  a: 1.310153, b: -0.109432, c: 0.002822, d: -0.060559, Throughput: 2.645968, Jitter: 0.006310, CM: -1.832236
9 ->  a: 1.311434, b: -0.119603, c: 0.001000, d: -0.060432, Throughput: 2.649720, Jitter: 0.006301, CM: -1.825513
10 ->  a: 1.310964, b: -0.129794, c: 0.001000, d: -0.060315, Throughput: 2.649720, Jitter: 0.006292, CM: -1.821264
11 ->  a: 1.310370, b: -0.139946, c: 0.001000, d: -0.060243, Throughput: 2.649720, Jitter: 0.006285, CM: -1.817841
12 ->  a: 1.309692, b: -0.150178, c: 0.001000, d: -0.060210, Throughput: 2.649720, Jitter: 0.006280, CM: -1.815103
13 ->  a: 1.308956, b: -0.160379, c: 0.001000, d: -0.060198, Throughput: 2.649720, Jitter: 0.006275, CM: -1.812811
14 ->  a: 1.307893, b: -0.170553, c: 0.001000, d: -0.060203, Throughput: 2.645968, Jitter: 0.006272, CM: -1.812872
15 ->  a: 1.308679, b: -0.180514, c: 0.001000, d: -0.060239, Throughput: 2.649720, Jitter: 0.006269, CM: -1.809541
```

Ring Topology:

```
debar@MacBook-Air cmake-cache % cmake --build . --target scratch_Final_Ring
[  0%] Building CXX object scratch/CMakeFiles/scratch_Final_Ring.dir/Final_Ring.cc.o
[  0%] Linking CXX executable /Users/debar/ns-3-allinone/ns-3-dev/build/scratch/ns3-dev-Final_Ring-default
debar@MacBook-Air cmake-cache % /Users/debar/ns-3-allinone/ns-3-dev/build/scratch/ns3-dev-Final_Ring-default


 ---- START ----

0 ->  a: 1.000000, b: 0.000000, c: 0.500000, d: 0.000000, Throughput: 14.379272, Jitter: 0.000410, CM: -6.984442
1 ->  a: 1.000000, b: 0.000000, c: 0.500000, d: 0.000000, Throughput: 14.379272, Jitter: 0.000751, CM: -6.814101
2 ->  a: 1.529335, b: -0.022577, c: 0.407287, d: -0.010555, Throughput: 16.223648, Jitter: 0.000947, CM: -7.638195
3 ->  a: 1.200531, b: -0.036263, c: 0.414047, d: -0.009557, Throughput: 15.099120, Jitter: 0.000933, CM: -7.082953
4 ->  a: 1.336802, b: -0.053179, c: 0.406826, d: -0.010438, Throughput: 15.590096, Jitter: 0.000950, CM: -7.319994
5 ->  a: 1.259365, b: -0.067267, c: 0.406171, d: -0.010473, Throughput: 15.333888, Jitter: 0.000952, CM: -7.191108
6 ->  a: 1.284043, b: -0.083534, c: 0.404274, d: -0.010690, Throughput: 15.419112, Jitter: 0.000956, CM: -7.231488
7 ->  a: 1.274079, b: -0.099037, c: 0.403321, d: -0.010788, Throughput: 15.374624, Jitter: 0.000958, CM: -7.208167
8 ->  a: 1.280018, b: -0.114503, c: 0.402429, d: -0.010883, Throughput: 15.403032, Jitter: 0.000960, CM: -7.221401
9 ->  a: 1.270343, b: -0.129679, c: 0.401823, d: -0.010944, Throughput: 15.374624, Jitter: 0.000962, CM: -7.206555
10 ->  a: 1.278264, b: -0.145119, c: 0.401236, d: -0.011004, Throughput: 15.403032, Jitter: 0.000963, CM: -7.220166
11 ->  a: 1.268643, b: -0.160277, c: 0.400826, d: -0.011043, Throughput: 15.374624, Jitter: 0.000963, CM: -7.205562
12 ->  a: 1.276603, b: -0.175703, c: 0.400400, d: -0.011086, Throughput: 15.403032, Jitter: 0.000964, CM: -7.219365
13 ->  a: 1.267010, b: -0.190851, c: 0.400097, d: -0.011113, Throughput: 15.366584, Jitter: 0.000965, CM: -7.200863
14 ->  a: 1.279012, b: -0.206779, c: 0.399744, d: -0.011149, Throughput: 15.403032, Jitter: 0.000966, CM: -7.218766
15 ->  a: 1.269435, b: -0.221921, c: 0.399511, d: -0.011169, Throughput: 15.374624, Jitter: 0.000966, CM: -7.204371
```

Star Topology:

```
debar@MacBook-Air cmake-cache % cmake --build . --target scratch_Final_Star
[  0%] Building CXX object scratch/CMakeFiles/scratch_Final_Star.dir/Final_Star.cc.o
[  0%] Linking CXX executable /Users/debar/ns-3-allinone/ns-3-dev/build/scratch/ns3-dev-Final_Star-default
debar@MacBook-Air cmake-cache % /Users/debar/ns-3-allinone/ns-3-dev/build/scratch/ns3-dev-Final_Star-default


 ---- START ----

0 ->  a: 1.000000, b: 0.000000, c: 0.500000, d: 0.000000, Throughput: 4.105760, Jitter: 0.000305, CM: 1.900454
1 ->  a: 1.000000, b: 0.000000, c: 0.500000, d: 0.000000, Throughput: 4.105760, Jitter: 0.001574, CM: 1.265823
2 ->  a: 0.477471, b: -0.044090, c: 0.033439, d: -0.049515, Throughput: 4.085928, Jitter: 0.002589, CM: 0.748468
3 ->  a: 0.193029, b: -0.052526, c: 0.001000, d: -0.056809, Throughput: 4.062344, Jitter: 0.002732, CM: 0.664944
4 ->  a: 0.208531, b: -0.051763, c: 0.001000, d: -0.056797, Throughput: 4.071992, Jitter: 0.002730, CM: 0.671173
5 ->  a: 0.221137, b: -0.052340, c: 0.001000, d: -0.056952, Throughput: 4.074136, Jitter: 0.002731, CM: 0.671802
6 ->  a: 0.232071, b: -0.054886, c: 0.001000, d: -0.057194, Throughput: 4.079496, Jitter: 0.002733, CM: 0.673192
7 ->  a: 0.241103, b: -0.058526, c: 0.001000, d: -0.057401, Throughput: 4.087536, Jitter: 0.002735, CM: 0.676361
8 ->  a: 0.247211, b: -0.062525, c: 0.001000, d: -0.057526, Throughput: 4.087536, Jitter: 0.002735, CM: 0.676149
9 ->  a: 0.253687, b: -0.065944, c: 0.001000, d: -0.057612, Throughput: 4.092896, Jitter: 0.002735, CM: 0.679013
10 ->  a: 0.257760, b: -0.069011, c: 0.001000, d: -0.057643, Throughput: 4.092896, Jitter: 0.002734, CM: 0.679614
11 ->  a: 0.262040, b: -0.072058, c: 0.001000, d: -0.057676, Throughput: 4.086464, Jitter: 0.002734, CM: 0.676446
12 ->  a: 0.269718, b: -0.074404, c: 0.001000, d: -0.057776, Throughput: 4.078424, Jitter: 0.002735, CM: 0.671653
13 ->  a: 0.281572, b: -0.076331, c: 0.001000, d: -0.057889, Throughput: 4.058056, Jitter: 0.002738, CM: 0.660251
14 ->  a: 0.303751, b: -0.077003, c: 0.001000, d: -0.058037, Throughput: 4.067168, Jitter: 0.002740, CM: 0.663386
15 ->  a: 0.321498, b: -0.077345, c: 0.001000, d: -0.058124, Throughput: 4.071992, Jitter: 0.002742, CM: 0.665067
```

Mesh Topology:

```
debar@MacBook-Air cmake-cache % cmake --build . --target scratch_Final_Mesh
[  1%] Building CXX object scratch/CMakeFiles/scratch_Final_Mesh.dir/Final_Mesh.cc.o
[  1%] Linking CXX executable /Users/debar/ns-3-allinone/ns-3-dev/build/scratch/ns3-dev-Final_Mesh-default
debar@MacBook-Air cmake-cache % /Users/debar/ns-3-allinone/ns-3-dev/build/scratch/ns3-dev-Final_Mesh-default


 ---- START ----

0 ->  a: 1.000000, b: 0.000000, c: 0.500000, d: 0.000000, Throughput: 3.965328, Jitter: 0.000722, CM: 1.621579
1 ->  a: 1.000000, b: 0.000000, c: 0.500000, d: 0.000000, Throughput: 3.965328, Jitter: 0.002098, CM: 0.933716
2 ->  a: 0.804800, b: -0.044798, c: 0.060657, d: -0.048099, Throughput: 3.944424, Jitter: 0.003115, CM: 0.414727
3 ->  a: 0.842446, b: -0.062104, c: 0.001000, d: -0.055979, Throughput: 3.953000, Jitter: 0.003285, CM: 0.333859
4 ->  a: 0.903158, b: -0.075697, c: 0.001000, d: -0.059124, Throughput: 3.957288, Jitter: 0.003354, CM: 0.301461
5 ->  a: 0.966544, b: -0.088784, c: 0.001000, d: -0.061129, Throughput: 3.968008, Jitter: 0.003398, CM: 0.285103
6 ->  a: 1.026025, b: -0.099586, c: 0.001000, d: -0.062390, Throughput: 3.957288, Jitter: 0.003426, CM: 0.265497
7 ->  a: 1.090963, b: -0.106182, c: 0.001000, d: -0.063294, Throughput: 3.948712, Jitter: 0.003448, CM: 0.250518
8 ->  a: 1.157440, b: -0.112277, c: 0.001000, d: -0.064070, Throughput: 4.028576, Jitter: 0.003464, CM: 0.282436
9 ->  a: 1.187175, b: -0.121378, c: 0.001000, d: -0.064511, Throughput: 4.029648, Jitter: 0.003473, CM: 0.278483
10 ->  a: 1.215522, b: -0.130743, c: 0.001000, d: -0.064921, Throughput: 4.025360, Jitter: 0.003481, CM: 0.271942
11 ->  a: 1.246753, b: -0.139526, c: 0.001000, d: -0.065302, Throughput: 4.033936, Jitter: 0.003490, CM: 0.272207
12 ->  a: 1.273015, b: -0.149402, c: 0.001000, d: -0.065689, Throughput: 4.035008, Jitter: 0.003497, CM: 0.268773
13 ->  a: 1.298785, b: -0.158789, c: 0.001000, d: -0.065999, Throughput: 4.032864, Jitter: 0.003504, CM: 0.264362
14 ->  a: 1.323154, b: -0.167110, c: 0.001000, d: -0.066291, Throughput: 4.030184, Jitter: 0.003510, CM: 0.259887
15 ->  a: 1.348553, b: -0.175932, c: 0.001000, d: -0.066568, Throughput: 4.048944, Jitter: 0.003516, CM: 0.266478
```