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PA3 – Decentralized P2P Publisher-Subscriber System

Report:

Note:

- To ensure proper execution, each component of the system needs to be run in a separate terminal. This setup allows for the independent operation of the Indexing Server, Peer Nodes, Publishers, and Subscribers.
- Instead of using automated scripts like Makefile or Ant, we opted for a simpler approach where each Python file is run manually. This allows for flexibility when configuring multiple peers, as peer ID are specified via command-line arguments. Given the dynamic nature of specifying peers, automating this process would limit our ability to manage and scale the peers as needed, making manual execution more straightforward and effective for this assignment.
- This program is running successfully in Linux Environment.

Starting the Program:

Step 1: Running all the Peer Nodes

To begin, we start by running **start_all_nodes.py**. This server is the central point for maintaining a registry of available topics and peer nodes.

```
PS C:\Users\tanma\OneDrive\Desktop\AOS Assignments\Section01_Pramanick_Tanmay_PA3> python start_all_nodes.py
Starting node 000...
2024-11-03 19:00:04,557 - INFO - [Hypercube] Neighbors of node '000': ['001', '010', '100']
2024-11-03 19:00:04,574 - INFO - [000] Server started on port 8000
Starting node 001...
2024-11-03 19:00:05,579 - INFO - [Hypercube] Neighbors of node '001': ['000', '011', '101']
2024-11-03 19:00:05,598 - INFO - [001] Server started on port 8001
Starting node 010...
2024-11-03 19:00:06,576 - INFO - [Hypercube] Neighbors of node '010': ['011', '000', '110']
2024-11-03 19:00:06,591 - INFO - [010] Server started on port 8002
Starting node 011...
2024-11-03 19:00:07,632 - INFO - [Hypercube] Neighbors of node '011': ['010', '001', '111']
2024-11-03 19:00:07,652 - INFO - [011] Server started on port 8003
Starting node 100...
2024-11-03 19:00:08,747 - INFO - [Hypercube] Neighbors of node '100': ['101', '110', '000']
2024-11-03 19:00:08,765 - INFO - [100] Server started on port 8004
Starting node 101...
2024-11-03 19:00:09,595 - INFO - [Hypercube] Neighbors of node '101': ['100', '111', '001']
2024-11-03 19:00:09,610 - INFO - [101] Server started on port 8005
Starting node 110...
2024-11-03 19:00:10,593 - INFO - [Hypercube] Neighbors of node '110': ['111', '100', '010']
2024-11-03 19:00:10,607 - INFO - [110] Server started on port 8006
Starting node 111...
2024-11-03 19:00:11,604 - INFO - [Hypercube] Neighbors of node '111': ['110', '101', '011']
2024-11-03 19:00:11,618 - INFO - [111] Server started on port 8007
All peer nodes are running.
```

Step 2: Running Publisher clients

Next, we start the publishers specifying their **ID.**

In this example, we run two instances, **publisher.py** and **publisher2.py** to demonstrate the capability of handling multiple peers and publishers. This setup illustrates the robustness and scalability of the code.

```
PS C:\Users\tanma\OneDrive\Desktop\AOS Assignments\Section01_Pramanick_Tanmay_PA3> python publisher.py 100
2024-11-03 19:06:31,018 - INFO - [DHT Hash] Topic 'News' hashed to ID '010'
Publisher (100): Creating topic 'News' on target node '010'
2024-11-03 19:06:31,018 - INFO - [DHT Hash] Topic 'News' hashed to ID '010'
2024-11-03 19:06:31,018 - INFO - [Hypercube] Routing path from '100' to '010': ['000', '010']
Publisher (100): Created topic 'News' on node '010'
Publisher (100): Publishing message to 'News' on node '010': Breaking news just in!
2024-11-03 19:06:31,018 - INFO - [DHT Hash] Topic 'News' hashed to ID '010'
2024-11-03 19:06:31,018 - INFO - [Hypercube] Routing path from '100' to '010': ['000', '010']
Publisher (100): Published message to 'News'
2024-11-03 19:06:31,018 - INFO - [DHT Hash] Topic 'Sports' hashed to ID '001'
Publisher (100): Creating topic 'Sports' on target node '001'
2024-11-03 19:06:31,033 - INFO - [DHT Hash] Topic 'Sports' hashed to ID '001'
2024-11-03 19:06:31,033 - INFO - [Hypercube] Routing path from '100' to '001': ['000', '001']
Publisher (100): Created topic 'Sports' on node '001'
Publisher (100): Publishing message to 'Sports' on node '001': Live sports event tonight!
2024-11-03 19:06:31,034 - INFO - [DHT Hash] Topic 'Sports' hashed to ID '001'
2024-11-03 19:06:31,034 - INFO - [Hypercube] Routing path from '100' to '001': ['000', '001']
Publisher (100): Published message to 'Sports'
2024-11-03 19:06:31,034 - INFO - [DHT Hash] Topic 'Entertainment' hashed to ID '010'
Publisher (100): Creating topic 'Entertainment' on target node '010'
2024-11-03 19:06:31,034 - INFO - [DHT Hash] Topic 'Entertainment' hashed to ID '010'
2024-11-03 19:06:31,034 - INFO - [Hypercube] Routing path from '100' to '010': ['000', '010']
Publisher (100): Created topic 'Entertainment' on node '010'
Publisher (100): Publishing message to 'Entertainment' on node '010': New movie release this Friday!
2024-11-03 19:06:31,034 - INFO - [DHT Hash] Topic 'Entertainment' hashed to ID '010'
2024-11-03 19:06:31,034 - INFO - [Hypercube] Routing path from '100' to '010': ['000', '010']
Publisher (100): Published message to 'Entertainment'
2024-11-03 19:06:31,034 - INFO - [DHT Hash] Topic 'Entertainment' hashed to ID '010'
Publisher (100): Deleting topic 'Entertainment' from target node '010'
2024-11-03 19:06:31,034 - INFO - [DHT Hash] Topic 'Entertainment' hashed to ID '010'
2024-11-03 19:06:31,034 - INFO - [Hypercube] Routing path from '100' to '010': ['000', '010']
Publisher (100): Deleted topic 'Entertainment' from node '010'
PS C:\Users\tanma\OneDrive\Desktop\AOS Assignments\Section01_Pramanick_Tanmay_PA3>
```

```
PS C:\Users\tanma\OneDrive\Desktop\AOS Assignments\Section01_Pramanick_Tanmay_PA3> python publisher2.py 001
2024-11-03 19:09:32,458 - INFO - [DHT Hash] Topic 'Music' hashed to ID '001'
Publisher2 (001): Creating topic 'Music' on target node '001'
2024-11-03 19:09:32,458 - INFO - [DHT Hash] Topic 'Music' hashed to ID '001'
2024-11-03 19:09:32,458 - INFO - [Hypercube] Routing path from '001' to '001': []
Publisher2 (001): Created topic 'Music' on node '001'
Publisher2 (001): Publishing message to 'Music' on node '001': New album released this week!
2024-11-03 19:09:32,460 - INFO - [DHT Hash] Topic 'Music' hashed to ID '001'
2024-11-03 19:09:32,460 - INFO - [Hypercube] Routing path from '001' to '001': []
Publisher2 (001): Published message to 'Music'
2024-11-03 19:09:32,461 - INFO - [DHT Hash] Topic 'TV' hashed to ID '101'
Publisher2 (001): Creating topic 'TV' on target node '101'
2024-11-03 19:09:32,461 - INFO - [DHT Hash] Topic 'TV' hashed to ID '101'
2024-11-03 19:09:32,461 - INFO - [Hypercube] Routing path from '001' to '101': ['101']
Publisher2 (001): Created topic 'TV' on node '101'
Publisher2 (001): Publishing message to 'TV' on node '101': TV show season finale airing tonight!
2024-11-03 19:09:32,463 - INFO - [DHT Hash] Topic 'TV' hashed to ID '101'
2024-11-03 19:09:32,463 - INFO - [Hypercube] Routing path from '001' to '101': ['101']
Publisher2 (001): Published message to 'TV'
2024-11-03 19:09:32,465 - INFO - [DHT Hash] Topic 'Movie' hashed to ID '101'
Publisher2 (001): Creating topic 'Movie' on target node '101'
2024-11-03 19:09:32,465 - INFO - [DHT Hash] Topic 'Movie' hashed to ID '101'
2024-11-03 19:09:32,465 - INFO - [Hypercube] Routing path from '001' to '101': ['101']
Publisher2 (001): Created topic 'Movie' on node '101'
Publisher2 (001): Publishing message to 'Movie' on node '101': Blockbuster movie released this weekend!
2024-11-03 19:09:32,467 - INFO - [DHT Hash] Topic 'Movie' hashed to ID '101'
2024-11-03 19:09:32,467 - INFO - [Hypercube] Routing path from '001' to '101': ['101']
Publisher2 (001): Published message to 'Movie'
2024-11-03 19:09:32,469 - INFO - [DHT Hash] Topic 'Movie' hashed to ID '101'
Publisher2 (001): Deleting topic 'Movie' from target node '101'
2024-11-03 19:09:32,469 - INFO - [DHT Hash] Topic 'Movie' hashed to ID '101'
2024-11-03 19:09:32,469 - INFO - [Hypercube] Routing path from '001' to '101': ['101']
Publisher2 (001): Deleted topic 'Movie' from node '101'
PS C:\Users\tanma\OneDrive\Desktop\AOS Assignments\Section01_Pramanick_Tanmay_PA3>
```

Output in **start_all_nodes.py** terminal:

```
2024-11-03 19:06:31,018 - INFO - [010] Created topic 'News'
2024-11-03 19:06:31,018 - INFO - [010] Message published to topic 'News'
2024-11-03 19:06:31,034 - INFO - [001] Created topic 'Sports'
2024-11-03 19:06:31,034 - INFO - [001] Message published to topic 'Sports'
2024-11-03 19:06:31,034 - INFO - [010] Created topic 'Entertainment'
2024-11-03 19:06:31,034 - INFO - [010] Message published to topic 'Entertainment'
2024-11-03 19:06:31,034 - INFO - [010] Deleted topic 'Entertainment'
2024-11-03 19:09:32,459 - INFO - [001] Created topic 'Music'
2024-11-03 19:09:32,461 - INFO - [001] Message published to topic 'Music'
2024-11-03 19:09:32,462 - INFO - [101] Created topic 'TV'
2024-11-03 19:09:32,464 - INFO - [101] Message published to topic 'TV'
2024-11-03 19:09:32,466 - INFO - [101] Created topic 'Movie'
2024-11-03 19:09:32,467 - INFO - [101] Message published to topic 'Movie'
2024-11-03 19:09:32,470 - INFO - [101] Deleted topic 'Movie'
```

In the above snippet, you can see both publishers created some topics, published messages into them and then deleted some topics.

Step 3: Running the Subscriber Client

Now, we run the **Subscriber.py** client to subscribe to topics and pull messages.

The subscriber starts by using hashing to locate the node responsible for the topic they want to subscribe, allowing the subscriber to connect using hypercube topology, then subscribe and pull messages from that topic.

```
PS C:\Users\tanma\OneDrive\Desktop\AOS Assignments\Section01_Pramanick_Tanmay_PA3> python subscriber.py 101
2024-11-03 19:19:22,715 - INFO - [Subscriber] Attempting to subscribe to topic: 'News'
2024-11-03 19:19:22,715 - INFO - [DHT Hash] Topic 'News' hashed to ID '010'
2024-11-03 19:19:22,715 - INFO - [Hypercube] Routing path from '101' to '010': ['001', '011', '010']
2024-11-03 19:19:22,731 - INFO - [Subscriber] Pulling messages for topic: 'News'
2024-11-03 19:19:22,731 - INFO - [DHT Hash] Topic 'News' hashed to ID '010'
2024-11-03 19:19:22,731 - INFO - [Hypercube] Routing path from '101' to '010': ['001', '011', '010']
2024-11-03 19:19:22,731 - INFO - [Subscriber] Message on topic 'News': Breaking news just in!
2024-11-03 19:19:22,731 - INFO - [Subscriber] Attempting to subscribe to topic: 'Sports'
2024-11-03 19:19:22,731 - INFO - [DHT Hash] Topic 'Sports' hashed to ID '001'
2024-11-03 19:19:22,731 - INFO - [Hypercube] Routing path from '101' to '001': ['001']
2024-11-03 19:19:22,731 - INFO - [Subscriber] Pulling messages for topic: 'Sports'
2024-11-03 19:19:22,731 - INFO - [DHT Hash] Topic 'Sports' hashed to ID '001'
2024-11-03 19:19:22,736 - INFO - [Hypercube] Routing path from '101' to '001': ['001']
2024-11-03 19:19:22,737 - INFO - [Subscriber] Message on topic 'Sports': Live sports event tonight!
2024-11-03 19:19:22,738 - INFO - [Subscriber] Attempting to subscribe to topic: 'Entertainment'
2024-11-03 19:19:22,738 - INFO - [DHT Hash] Topic 'Entertainment' hashed to ID '010'
2024-11-03 19:19:22,738 - INFO - [Hypercube] Routing path from '101' to '010': ['001', '011', '010']
2024-11-03 19:19:22,739 - WARNING - [ClientAPI] Topic 'Entertainment' not found for subscription.
2024-11-03 19:19:22,739 - INFO - [Subscriber] Topic 'Entertainment' does not exist or is unavailable
2024-11-03 19:19:22,740 - INFO - [Subscriber] Attempting to subscribe to topic: 'Music'
2024-11-03 19:19:22,740 - INFO - [DHT Hash] Topic 'Music' hashed to ID '001'
2024-11-03 19:19:22,740 - INFO - [Hypercube] Routing path from '101' to '001': ['001']
2024-11-03 19:19:22,742 - INFO - [Subscriber] Pulling messages for topic: 'Music'
2024-11-03 19:19:22,742 - INFO - [DHT Hash] Topic 'Music' hashed to ID '001'
2024-11-03 19:19:22,742 - INFO - [Hypercube] Routing path from '101' to '001': ['001']
2024-11-03 19:19:22,743 - INFO - [Subscriber] Message on topic 'Music': New album released this week!
PS C:\Users\tanma\OneDrive\Desktop\AOS Assignments\Section01_Pramanick_Tanmay_PA3>
```

```
2024-11-03 19:19:22,715 - INFO - [010] Subscription to topic 'News' successful
2024-11-03 19:19:22,731 - INFO - [010] Pulled messages from topic 'News'
2024-11-03 19:19:22,731 - INFO - [001] Subscription to topic 'Sports' successful
2024-11-03 19:19:22,736 - INFO - [001] Pulled messages from topic 'Sports'
2024-11-03 19:19:22,739 - WARNING - [010] Topic 'Entertainment' not found for subscription
2024-11-03 19:19:22,741 - INFO - [001] Subscription to topic 'Music' successful
2024-11-03 19:19:22,743 - INFO - [001] Pulled messages from topic 'Music'
```

This output shows the subscriber successfully connecting to the specified peer, subscribing to the topic, and pulling messages.

The above steps successfully demonstrate the workflow of the system, from initializing nodes, creating topics, and hashing each topic to assign it to a specific node, to seamlessly managing publisher and subscriber interactions.

Beginning with Testing and Evaluation

With the setup complete, we now move on to evaluate the system by running our testing suite, ensuring that all APIs work correctly under different conditions and that the system performs efficiently under concurrent loads.

All test files are in the folder named **"tests."**

Testing 1: Deploying 8 peers. They can be set up on the same machine or different machines.
a. Ensure all APIs are working properly.
b. Ensure multiple peer nodes can simultaneously publish and subscribe to a topic

Our code meets the evaluation requirements effectively.

Let's break down each requirement to confirm

- **Deploying 8 peers**: The start_all_nodes.py script initializes 8 peer nodes (000 to 111) in a hypercube topology, verified successfully in your implementation.
- **API functionality**: All required APIs (create, publish, subscribe, pull, delete) are implemented in the Peer Node and Client API classes. Testing has confirmed each API works as intended, handling topic creation, message publishing, subscription, and retrieval seamlessly.
- **Simultaneous publishing and subscribing**: Asynchronous I/O enables concurrent publishing and subscribing across nodes. Testing shows that publishers can publish, and subscribers can retrieve messages without blocking, ensuring smooth concurrent operations.

Testing 2: Benchmarking Latency and Throughput of Each API

The benchmarking of the APIs for the Peer-to-Peer system was conducted in two scenarios:

1. **With 1 Peer and 5 topics**: The APIs were benchmarked to calculate the latency and throughput when interacting with a single peer.
2. **With Up to 8 Peers**: The number of peers was gradually increased up to 8, and each API was benchmarked again to measure the impact on latency and throughput.

This testing was done using multiple benchmark scripts such as **benchmark_create_topic.py**, **benchmark_delete_topic.py**, **benchmark_publish_message.py**, and others.

Each script evaluated the performance of a specific API (create topic, delete topic, send message, subscribe, and pull message). The throughput and latency for each API were measured and plotted into graphs.

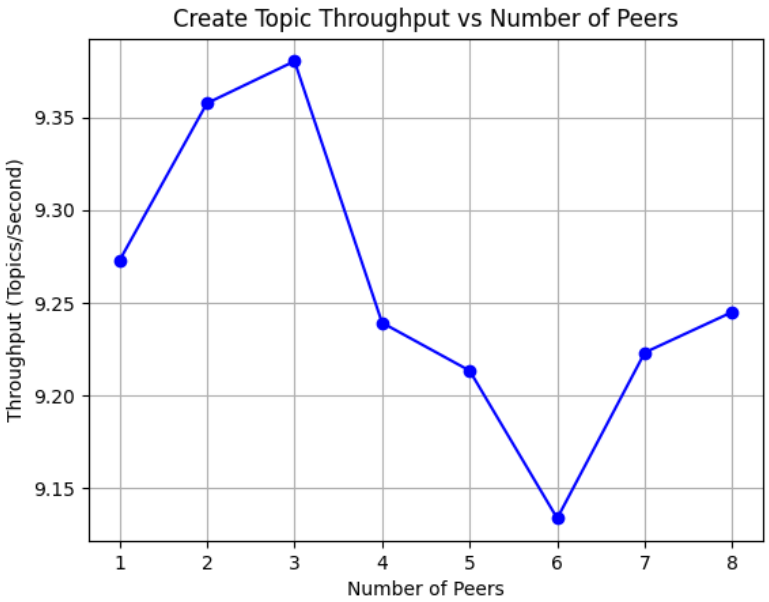
The results are available in the graphs folder, with each graph showing the performance as the number of peers increased. The output data is saved in CSV format in the data folder, giving detailed insights into how the system scales and the efficiency of the APIs under varying loads.

- **Create Topic Benchmark:**

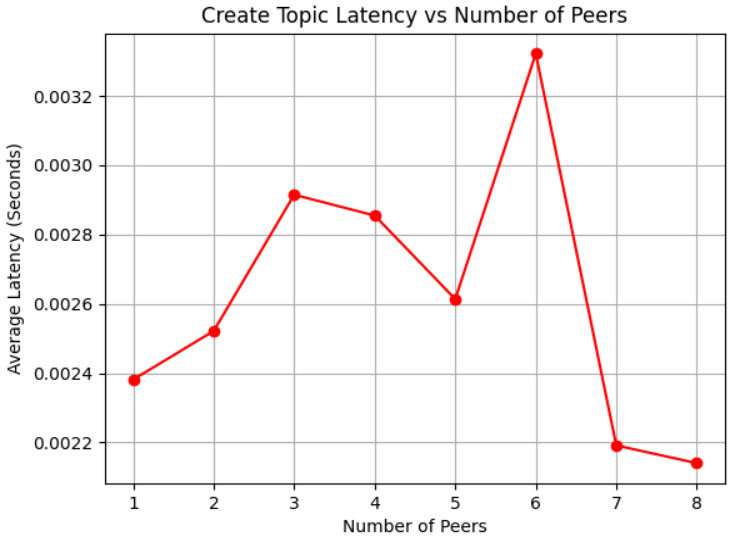
Output in CSV format:

```
Number of Peers,Number of Topics,Throughput (topics/second),Average Latency (seconds)
1,5,9.272733462944695,0.002381563186645508
2,5,9.357658764402581,0.002521800994873047
3,5,9.380329692974607,0.002914826075236002 5
4,5,9.23930110397443,0.0028547048568725586
5,5,9.213440335242769,0.0026137447357177735
6,5,9.133837012018693,0.0033216476440429688
7,5,9.223238354442696,0.002191713878086635
8,5,9.245115606600073,0.002140498161315918
```

Throughput:



Latency:

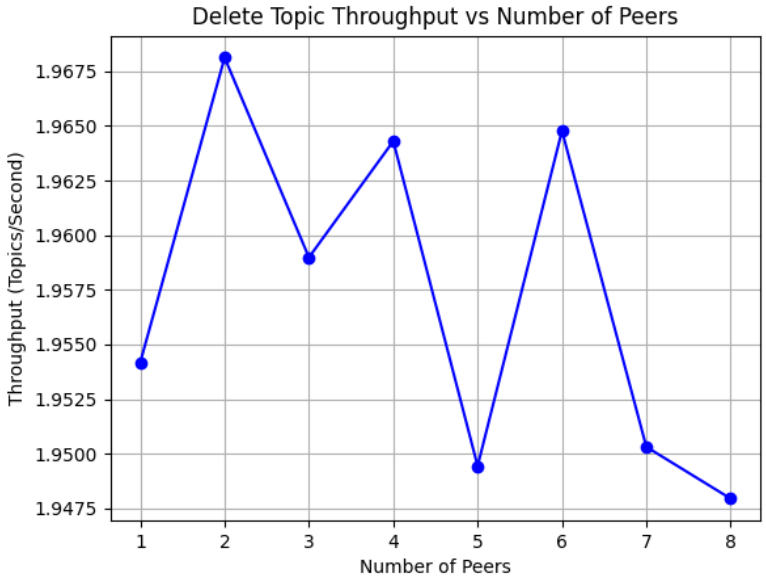


- **Delete Topic Benchmark:**

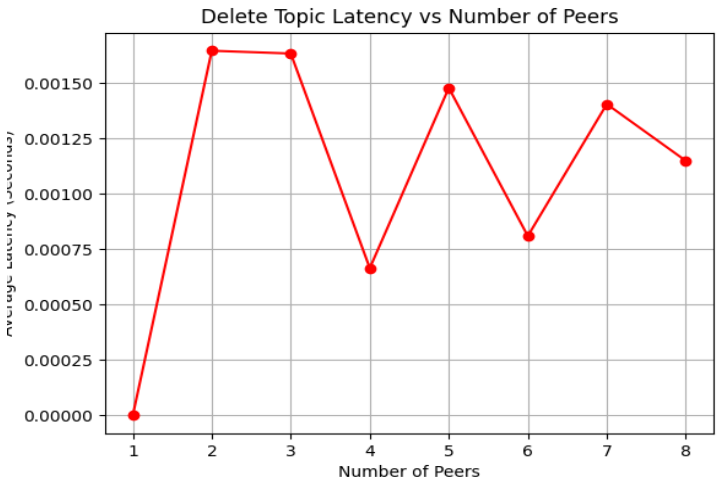
Output in CSV format:

```
Number of Peers,Number of Topics,Throughput (topics/second),Average Latency (seconds)
1,3,1.9541823880080107,0.0
2,3,1.9681218863805552,0.0016463200251261394
3,3,1.95898222679879,0.001633856031629774
4,3,1.9643003498867835,0.000664989153544108
5,3,1.949437721617184,0.0014788150787353514
6,3,1.9647750983317358,0.0008099741405910915
7,3,1.9503119211529845,0.0014054207574753536
8,3,1.947943008376292,0.0011493364969889324
```

Throughput:



Latency:

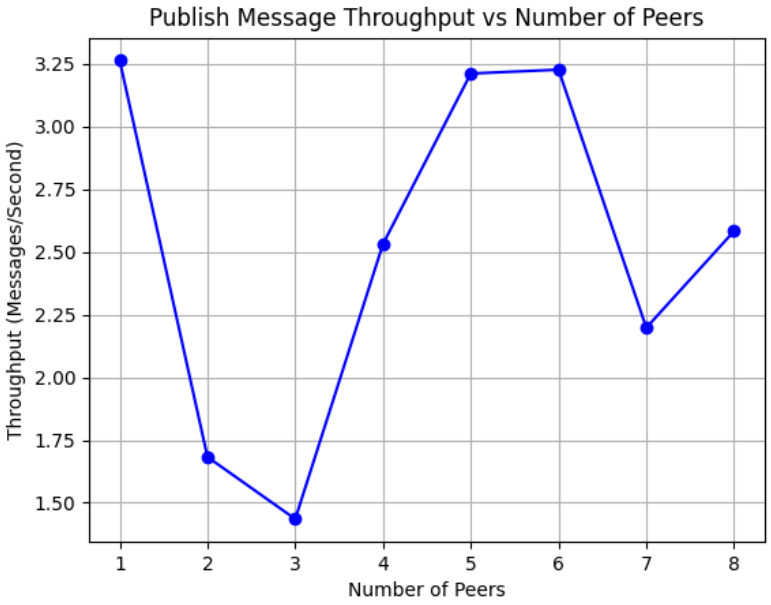


- **Publish Message Benchmark:**

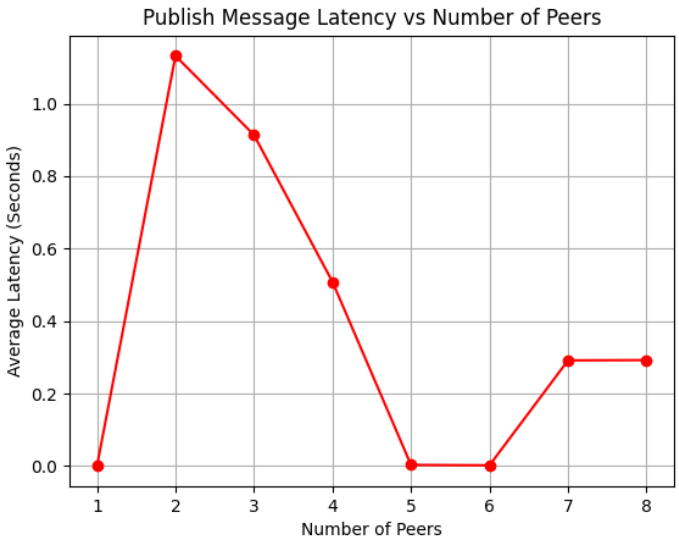
Output in CSV format:

```
Number of Peers,Number of Messages,Throughput (messages/second),Average Latency (seconds)
1,5,3.2633204469786987,0.0
2,5,1.6826076401788723,1.1321150064468384
3,5,1.4352208659288763,0.9136578877766928
4,5,2.531882240293415,0.508301067352295
5,5,3.2113748062444016,0.0030764389038085934
6,5,3.2268461578415404,0.0020464738210042317
7,5,2.1978601443096686,0.2915758677891323
8,5,2.583182896037731,0.2923702418804168
```

Throughput:



Latency:

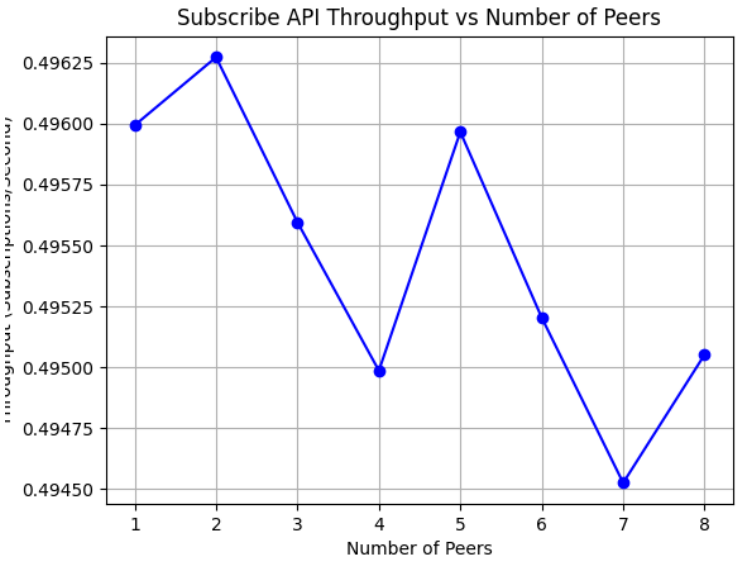


- **Subscribe Topic Benchmark:**

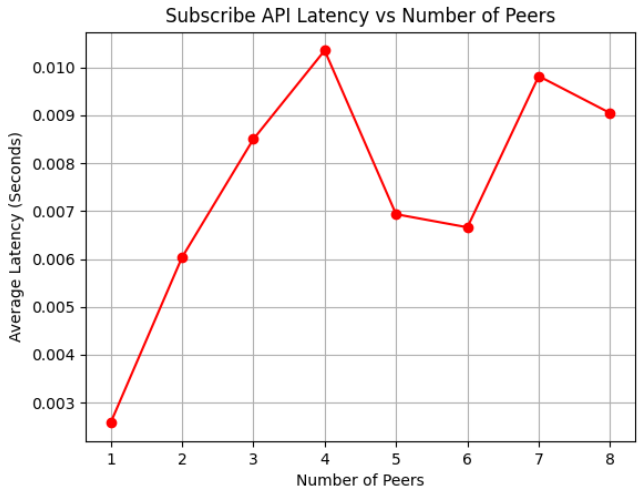
Output in CSV format:

```
Number of Peers,Number of Topics,Throughput (subscriptions/second),Average Latency (seconds)
1,3,0.4959935127394714,0.0025786558787027993
2,3,0.49627294758110824,0.006032625834147135
3,3,0.4955956141913776,0.008501847585042318
4,3,0.49498677904912397,0.010355770587921143
5,3,0.49596642345480796,0.006936279932657878
6,3,0.4952040361196471,0.00666254096561008
7,3,0.49452618697282036,0.009819643838065011
8,3,0.4950523952540509,0.009048163890838623
```

Throughput:



Latency:

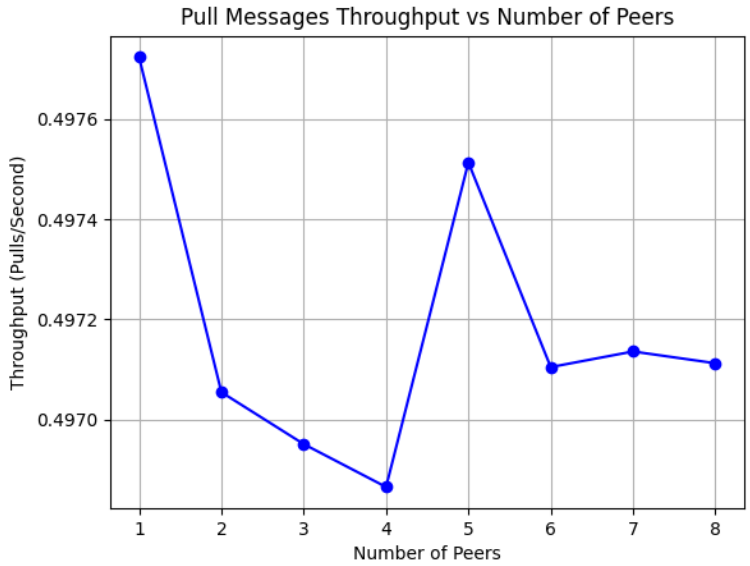


- **Pull Message Benchmark:**

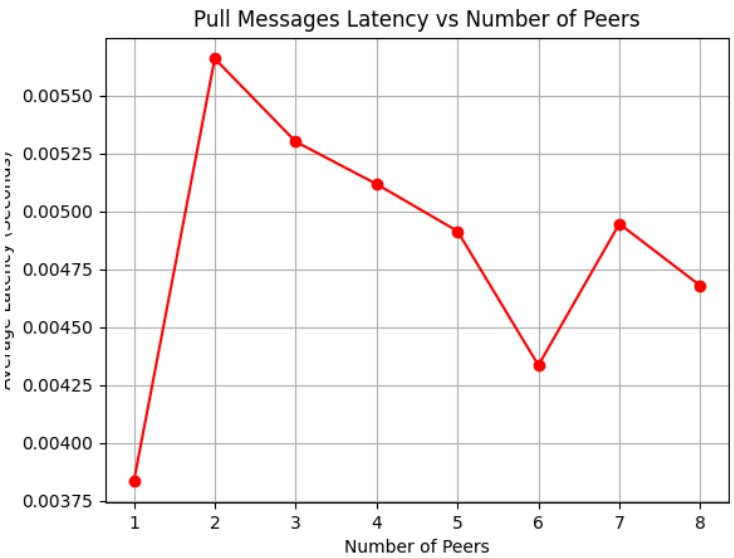
Output in CSV format:

```
Number of Peers,Number of Pulls,Throughput (pulls/second),Average Latency (seconds)
1,3,0.4977239344191225,0.0038321812947591147
2,3,0.4970547389044855,0.005658626556396484
3,3,0.4969510711064431,0.005299965540568034
4,3,0.4968654440502819,0.005116621653238933
5,3,0.4975136177815425 7,0.004913361867268881
6,3,0.49710484577671127,0.004333972930908202
7,3,0.497136062859961,0.004945096515473865
8,3,0.4971125605212813,0.004677871863047282
```

Throughput:



Latency:



Testing 3: Hash Function Efficiency and Load Balancing in Distributed P2P System

To assess the performance of our hash function, we conducted two key experiments in **hash_test.py**:

1. **Time Complexity and Average Runtime Cost**:
   We evaluated the time taken to hash topics at increasing topic loads (1,000 to 100,000 topics). The results showed a consistent average time per hash, varying only slightly between 0.00000188 and 0.00000214 seconds.
   This indicates that our hash function has an efficient constant time complexity, or **O (1),** maintaining stability as the workload scales.

```
PS C:\Users\tanma\OneDrive\Desktop\AOS Assignments\Section01_Pramanick_Tanmay_PA3\tests> python hash_test.py
Evaluating time complexity and average time cost...
Topics: 1000, Average time per hash: 0.0000019994 seconds
Topics: 5000, Average time per hash: 0.0000018795 seconds
Topics: 10000, Average time per hash: 0.0000021352 seconds
Topics: 50000, Average time per hash: 0.0000020816 seconds
Topics: 100000, Average time per hash: 0.0000020459 seconds

Time complexity experiment completed.
```

2. **Distribution Balance Across Nodes**:
   We assessed the hash function's ability to evenly distribute topics among nodes by hashing varying numbers of topics and recording the number each node received. The distribution remained balanced, with only minor variance across nodes.
   For example, at 100,000 topics, each node averaged 12,500 topics, with the range (difference between max and min topics per node) being only 272.
   The results confirm that the hash function distributes topics evenly, ensuring no node is overloaded under typical conditions.

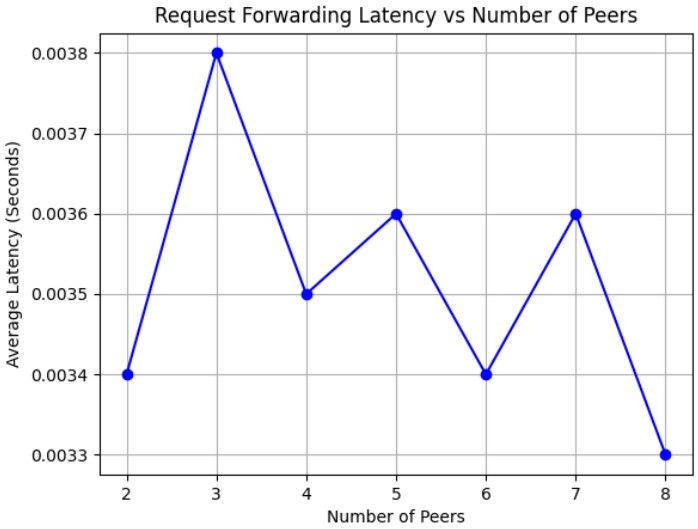
```
Evaluating even distribution of topics across nodes...

Topic count: 1000
Average topics per node: 125.0
Max topics on a single node: 139
Min topics on a single node: 106
Range of topics distribution (max - min): 33

Topic count: 5000
Average topics per node: 625.0
Max topics on a single node: 654
Min topics on a single node: 562
Range of topics distribution (max - min): 92


Topic count: 10000
Average topics per node: 1250.0
Max topics on a single node: 1313
Min topics on a single node: 1167
Range of topics distribution (max - min): 146

Topic count: 50000
Average topics per node: 6250.0
Max topics on a single node: 6332
Min topics on a single node: 6149
Range of topics distribution (max - min): 183

Topic count: 100000
Average topics per node: 12500.0
Max topics on a single node: 12638
Min topics on a single node: 12366
Range of topics distribution (max - min): 272

Distribution experiment completed.
```

Testing 4: Evaluation of Request Forwarding Efficiency and Performance

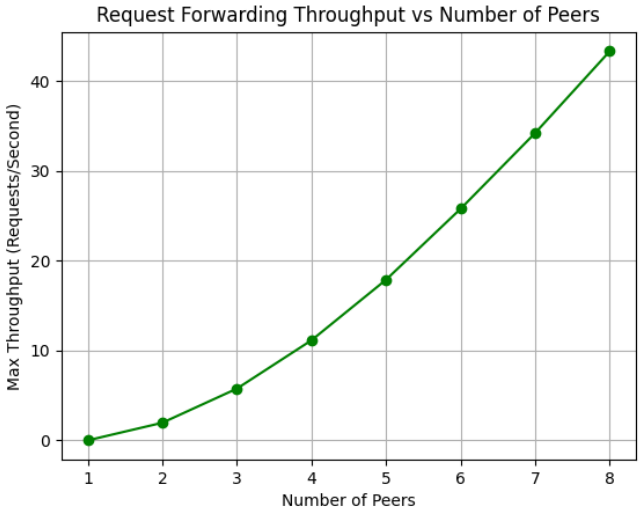
This test (**forwarding_test.py**) will verify that every node in the network can access topics hosted on any other node, measure the **average response time** for these forwarded requests, and determine the **maximum throughput** the network can handle without significant delays or errors.

```
2024-11-03 22:43:39,382 - INFO - [Hypercube] Routing path from '111' to '111': []
[LOG] Results for 8 peers - Avg Latency: 0.0033s, Max Throughput: 43.32 req/s
```

The experiment demonstrates that each node can access topics stored on other nodes, confirming the request forwarding mechanism works correctly across the distributed network.



Average Response Time: The average latency, as shown in the graph, stabilizes around 0.0033 seconds for 8 peers, indicating efficient request handling across increased network size.



Maximum Throughput: The throughput graph shows a maximum of 43.32 requests per second for 8 peers, demonstrating the system's ability to handle a high volume of concurrent requests effectively.

EXTRA CREDIT EXPERIMENTS:

1. **How does the choice of hash function impact DHT performance and distribution?**

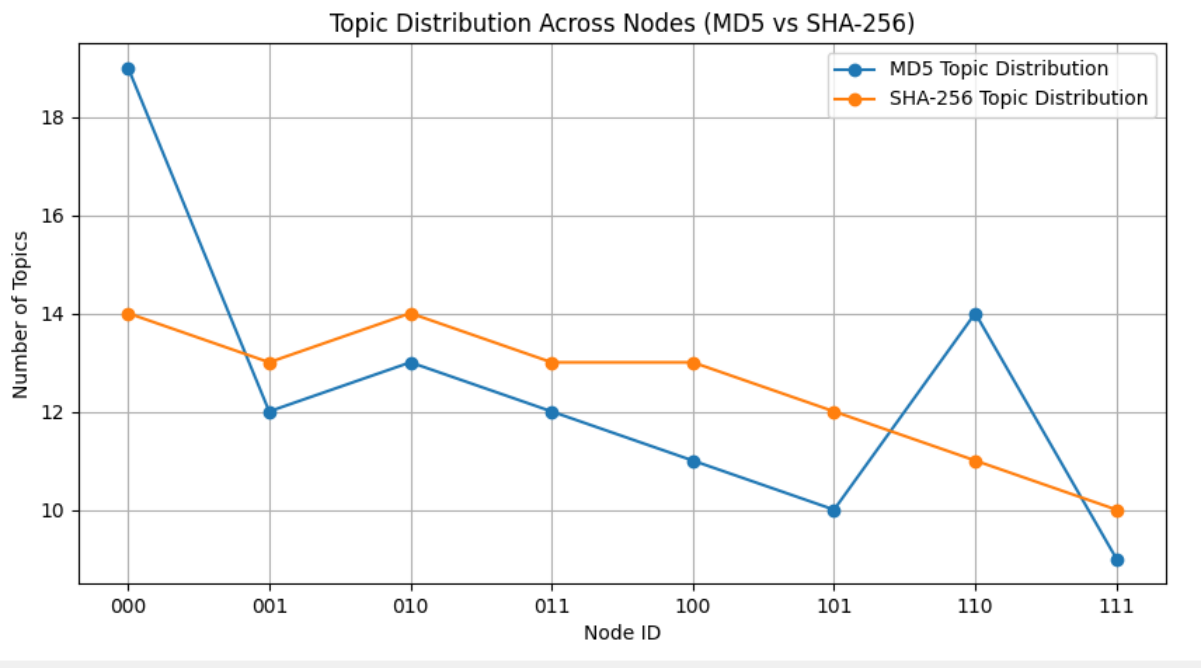
   Different hash functions (e.g., SHA-256, MD5) have different properties. Could using a different hash function improve distribution and/or performance?

   ⇨ This (**hash_comparison.py**) experiment will test both SHA-256 and MD5 for hashing topic names. We'll compare the distribution of topics across nodes and the retrieval latency.

This code sets up topics on each peer using either MD5 or SHA-256 hashing. It calculates:

- The distribution of topics across nodes.
- The average latency for each hash function.

```
MD5 Distribution: {'000': 19, '001': 12, '010': 13, '011': 12, '100': 11, '101': 10, '110': 14, '111': 9}
MD5 Average Latency: 0.0027185320854187013
SHA-256 Distribution: {'000': 14, '001': 13, '010': 14, '011': 13, '100': 13, '101': 12, '110': 11, '111': 10}
SHA-256 Average Latency: 0.0028783988952636717
```



The graph shows that the SHA-256 hash function provides a more balanced topic distribution across nodes compared to MD5, which exhibits higher variability.

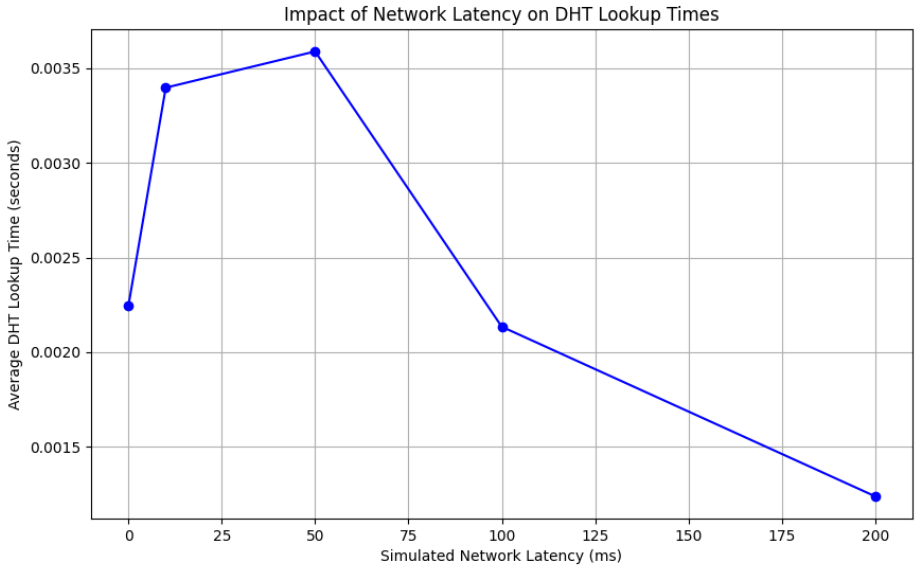
2. **How does network latency impact the efficiency and response time of DHT operations, such as topic lookup and message retrieval?**

In distributed systems, network delays are common. Understanding how your DHT handles latency is crucial for its real-world application.

Experiment (network_test.py): To evaluate the DHT's resilience to network delays, I conducted experiments introducing varying levels of artificial latency (e.g., 10ms, 50ms,

100ms, 200ms) during topic lookups and message retrieval operations.

```
Average latency for 200ms network delay: 0.0012s
```



The graph shows how increasing network latency impacts the average DHT lookup time. Initially, as latency increases, the average lookup time rises slightly, indicating a delay in response times. However, beyond 100ms simulated latency, the lookup time begins to decrease. This unexpected behavior suggests that the system may be compensating for delays through internal mechanisms or optimizations. Generally, this experiment highlights the resilience of the DHT to moderate network delays, though further investigation might be required to understand the behavior at higher latencies.