Exploring Routing Asymmetry in FABRIC

Krishnaprasad Palamattam Aji  
*School of Computing and Augmented Intelligence*  
*Arizona State University*  
[kpalamat@asu.edu](mailto:kpalamat@asu.edu)

*Abstract*— This paper presents an investigation into the routing asymmetry of FABRIC testbed. Asymmetric routing is when packets take one path to the destination and take a different path while returning to the source. Asymmetric routing is common within most networks. The larger the network, the more likely there's asymmetric routing in the network. The initial approach in the paper is to utilize Precision Time Protocol (PTP) to measure latency differences between a constrained set of host pairs, aiming to identify potential asymmetries by comparing one-way latencies (OWL) from point A to point B and back. Significant latency variations prompt further traceroute analysis to differentiate genuine path asymmetry from differences in interface IP addresses of the same router. We then try to quantify the asymmetry of such paths and identify the path between nodes that are most asymmetric. By the end of the experiment, we will be able to identify and quantify routing asymmetry between the nodes in FABRIC.

Keywords—FABRIC, Routing asymmetry, PTP, OWL, traceroute, Absolute Asymmetry, Normalized Asymmetry, Minimal Composite Dissimilarity.

# Introduction

Routing asymmetry refers to the phenomenon where the forward path taken by data packets from a source to the destination differs from the reverse path. It can happen due to a number of reasons, including differing network policies, topology changes and dynamic routing decisions.

Long term asymmetric routes are mainly created due to routing policies and traffic engineering [2]. Providers may prioritize moving packets destined for different networks out of their own network, even if it means longer paths or higher congestion, leading to hot potato routing and asymmetry at both link and autonomous system levels. Load balancing could also cause routing asymmetry where it shifts traffic from a heavily loaded link to a lightly loaded one to avoid congestion. The absence of a unique shortest path between two nodes can also cause asymmetry where routing protocols choose randomly from one of the many possible shortest paths.

Routing asymmetry causes a lot of challenges in the way we measure and model the network. Routing asymmetry disrupts network stability, causing packet loss and increased latency as packets traverse disparate paths. This inconsistency leads to unpredictable traffic behavior, complicating troubleshooting efforts and hindering fault isolation. Quality of Service (QoS) suffers due to the erratic traffic patterns, impacting service availability and performance. Moreover, security mechanisms reliant on consistent traffic flows may fail, leaving networks vulnerable to attacks such as IP spoofing or route hijacking.

Routing asymmetry also introduces potential inaccuracies in measuring the one way latency between hosts. The current practice is to estimate it as half of the round trip time (RTT) which is easier to calculate. This estimation becomes worse as the asymmetry increases. Inaccurate one-way latency estimates can misguide communication timing, causing delays and timeouts which degrades performance in networks. Quality of Service (QoS) metrics like throughput and jitter is also affected, impacting user experiences. Faulty estimates mislead congestion control and routing decisions, exacerbating congestion and packet loss. Protocols relying on precise timing also become unstable, potentially causing network instability or protocol violations. Troubleshooting becomes challenging, as discrepancies obscure performance issues, necessitating accurate latency measurement for optimal network operation and user satisfaction.

The goal of this project is to identify the existence of routing asymmetry in the FABRIC [1] testbed and to quantify the asymmetry of such paths. We utilize Precision Time Protocol (PTP) to measure the one-way latencies (OWL) between nodes A and B. A significant difference in the OWL might be an indication of asymmetric routing between the two nodes. We identify such pair of nodes and prompt further traceroute analysis to differentiate genuine path asymmetry from differences in interface IP addresses of the same router. Traceroute is a reliable method to identify routing asymmetry as discussed in [7].

The following sections talk about the background and motivation for the paper, related work done in asymmetric routing in different networks and the learnings from it, the experiments performed, result and finally the conclusion to the paper.

# Background and Motivation

## Background

In the realm of network communications, the data packet flow from the source to destination is governed by routing protocols. These protocols decide the path the packets take to increase efficiency, speed and reliability of the network [11][12]. While symmetric routing is often idealized, that is not always the reality. Asymmetric routing, characterized by divergent paths for outgoing and incoming packets, is a common phenomenon across networks.

The Precision Time Protocol (PTP), designed for precise time synchronization over a network, plays a pivotal role in measuring one-way latencies (OWL). Such measurements are crucial for detecting routing asymmetry, offering a more nuanced understanding of network performance beyond traditional round-trip time (RTT) metrics.

An asymmetric routing study has extensively been performed on the Internet and other networks by de Vries et al. [7]. They were able to confirm the presence of asymmetry in a majority of the routes on the internet and also where this asymmetry occurs. A differentiation between genuine asymmetry in the network from the differences in interface IPs of the same router is given in [2]. They also talk in detail about finding the minimal composite dissimilarity, absolute asymmetry and normalized asymmetry between a pair of paths. They are therefore able to quantify asymmetry in such paths. Differences in path lengths and OWL between two nodes are indicators of asymmetrical networks but it is not conclusive evidence of asymmetry. They can help in reducing the sample size of nodes to further study routing asymmetry.

Traceroute method is still reliable in identifying routing asymmetry of networks, and various probe methods using ICMP and TCP is studied in [3].

## Motivation

Routing asymmetry is important in the way we measure, model and manage the network. Traditional metrics like RTT to find approximate one way latencies between nodes are less reliable in asymmetrical networks highlighting the need for innovative measurement techniques [7].

There have been many studies on routing asymmetry of the internet previously done by researchers. In this project we try to carry this out on FABRIC. Identifying network asymmetry is difficult when we do not have administrative control or influence over the destination network or device being probed. Traceroutes only help us in finding the route to the destination but not the reverse path. Katz-Bassett et al [8] uses a variety of measurement techniques to incrementally piece together the path from the destination back to the source which is a complex process. We try to make use of FABRIC, where we have control over destination nodes to identify the existence of asymmetrical routing within the network. By doing this we will be able to identify and quantify the asymmetry of such paths within FABRIC.

# Research

The research for this project includes finding one-way latency (OWL) between two nodes on fabric, probing using traceroute methods, identifying genuine asymmetry from traceroutes and also quantifying routing asymmetry in FABRIC.

## OWL measurement with PTP

FABRIC has a total of 33 sites (29 in the US and 4 international sites) [9]. Out of these, 10 sites have GPS-disciplined clocks which make use of PTP for various measurements. OWL (One-way Latency) is a network latency measurement tool developed specifically for experiments leveraging the PTP (precision time protocol) on FABRIC testbed.

It is different from the traditional method for calculating RTT because it timestamps a UDP packet when it leaves the source node and again when it is received at the destination node. The Precision Time Protocol (PTP) is a protocol used to synchronize clocks throughout a computer network. On a local area network, it achieves clock accuracy in the sub-microsecond range, making it suitable for measurement and control systems [9]. This method provides accurate one-way latency measurements, enabling the assessment of individual segments of the RTT journey.

The KNIT6\_MFLIB Jupyter notebook tutorials and the GitHub repository on measurement frameworks were also very useful to understand PTP and OWL measurement on FABRIC.

## Traceroute Analysis

The traceroute command when executed from node A to node B shows the paths that the data packets take from A to B. Table 2 shows the values from a traceroute between STAR and CERN. Here we can see that there are 4 hops, meaning there were 4 network devices encountered on the path from STAR to CERN. Three packets were sent to the devices at each hop and the RTT is calculated and shown as Latency 1,2 and 3. The normal traceroute probe shows the other routers that are available from a particular hop. Table 3 which shows the reverse path from CERN to STAR contains two routers at hop 2. The path chosen by the packet was the first IP address mentioned in hop 2 which has a lower latency value as well. But while comparing Table 1 and Table 3, we can see that none of the IP addresses are same in the forward or reverse path. We next discuss a method to identify genuine asymmetry from differences in interfaces of the same router.

## Identifying Genuine Asymmetry

A diagram of a algorithm

Description automatically generated

Fig 1: Traceroute probing router interfaces

Fig. 1 shows a network with routers R1, R2, R3, and R4 between two nodes A and B. Here, b and c are different interfaces of the same router R1 and we cannot simply match the IP addresses in the forward and reverse directions to establish asymmetry. Suppose the forward path taken from A to B is (b, d, f and h). In case of symmetrical routing the reverse path taken from B to A will be (g, e, c, and a). A genuine case of asymmetry occurs when the reverse path from B to A is (g, j, i, and a). He et al. [2] describes in detail about genuine asymmetry and the mere difference in interface IPs of the same router. In short, if the IPs only differ by 1 in the last octet, they are just different interfaces of the same router.

## Quantifying Asymmetry

A diagram of a diagram

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Fig 2: Simple asymmetry cases and their minimal composite dissimilarity

We will discuss the approach to quantify routing asymmetry between forward and reverse paths between two hosts [6]. We will talk about Absolute Asymmetry and length-based Normalized Asymmetry.

To quantify asymmetry between two paths, we find the dissimilarity of entities in the two paths considered in a sequence. It is very similar to comparing sequences of genes in computational biology where string matching techniques are used. Motivated by this approach, we measure the dissimilarity between a pair of routes by aligning the two routes together and measuring the minimal total cost incurred in aligning them.

We consider the paths between two hosts X and Y. The forward path contains m entities and is represented by u where

***u*** = (u1, u2, u3, … , um) (1)

The reverse path from Y to X containes n entities and is represented by v where

***v*** = (vn, vn-1, vn-2, … , v1) (2)

We now define , that sequentially maps all indices in path ***u*** to the set of indices of a subset of ***v***. Similarly, ’ sequentially maps all indices in path ***v*** to the set of indices of a subset of ***u.***

For any two entities x and y in a set S, we define a nonnegative base dissimilarity value which represents the magnitude of how much x is different from y. The value will be zero if and greater than 0 when . Here we use dissimilarity value 1 when . The set of such values for all entity pairs in S forms a base dissimilarity matrix.

(3)

The composite dissimilarity of a pair of sequential mappings between two paths is denoted by

where composite dissimilarity is the sum of dissimilarity in the mappings of ***u*** to ***v*** () and ***v*** to ***u*** ().

We define as the minimal composite dissimilarity for all possible mappings between ***u*** and ***v***:

and the mapping pair is called the optimal mapping pair.

Now let us describe how we use this in Fig. 2. In Fig. 2a one of the optimal mappings is for and for . This is an example where path lengths of forward and reverse paths are different and hence the number of mappings in is 4 and in is 3. Here the only mismatch is in the forward path mapping. Hence the minimum dissimilarity is 1.

Similarly, in Fig. 2b the optimal mappings are for and for . But in this case, the mismatches are in the forward path and in the reverse path and the minimum composite dissimilarity is 2.

Using this approach, we can calculate the dissimilarity in Fig. 2c as 6. Here the approach is to find dissimilarity of mappings in forward to reverse path and vice versa and to sum them up.

In simple words, the dissimilarity between two paths can be measured as the minimal total cost incurred in aligning them. In Fig. 2a forward and reverse paths differ by 1 entity. If we are to add entity C in the reverse path, both the paths would be similar. Hence the dissimilarity here is 1. Similarly in Fig. 2b, we can make the forward and reverse paths equal by performing 2 actions, either removing C and adding E in the forward path or removing E and adding C in the reverse path. In each case we need to perform 2 actions (adding an entity and removing an entity). Hence the dissimilarity is 2.

**Absolute Asymmetry** is defined as the minimum composite dissimilarity between a pair of forward and reverse paths u and v.

We see that AA in Fig. 2a is 1 and in Fig. 2b is 2. Does this mean that configuration in Fig. 2a has more symmetry than the one in Fig. 2b? To address this, we try to find **Normalized Asymmetry** between pairs of forward and reverse paths.

Hence NA in Fig. 2a will be 1/(4+3) = 0.14, and in Fig. 2b will be 2/(4+4) = 0.25. Similarly, in Fig. 2c it will be 6/(5 +5) =0.6.

From the above calculations we can understand that

When the forward and reverse paths are the same, NA(u,v) will be 0, and when forward and reverse paths are completely different, NA(u,v) will be 1.

# Experiment

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Description automatically generated with medium confidence

Fig 3: Nodes that were used as part of the experiment to calculate OWL

The experiment makes use of the resources provided by FABRIC which has a total of 10 sites that have GPS-disciplined clocks. The FABRIC sites that are currently PTP compatible are STAR, MAX, MICH, MASS, UTAH, NCSA, UCSD, FIU, CLEM, and CERN. Nodes are created on these sites with basic NICs connected to FABRIC's FABnetv4 internet as shown in Fig. 3.

The experiment starts with creating a slice with 10 nodes in each of the above-mentioned sites. PTP is then setup in these sites making use of the Measurement Framework GitHub repository. The OWL experiments make use of Docker containers having multiple “owl-senders” at the source site and an “owl-capturer” at each destination site. The experiment was run for 500 seconds, and we obtained a packet-capture (PCAP) file at each owl-capturer containing around 6000 UDP packets. An OWLDataAnalyzer given by the OWL framework is used to analyze the PCAP file from each of the 10 sites. Table 1 provides the measurements of one-way latency between sites, with the data ordered in decreasing order based on the absolute difference between the forward and reverse one-way latency measurements.

|  |  |  |  |
| --- | --- | --- | --- |
| Source | Destination | OWL (ms) | difference |
| CLEM | CERN | 63.29 | 9.86 |
| CERN | CLEM | 53.43 |
| STAR | CERN | 51.85 | 8.44 |
| CERN | STAR | 60.29 |
| CERN | MASS | 50.98 | 5.28 |
| MASS | CERN | 56.26 |
| CERN | UTAH | 67.86 | 4.91 |
| UTAH | CERN | 72.77 |
| CERN | NCSA | 63.23 | 4.77 |
| NCSA | CERN | 58.46 |
| CERN | MICH | 64.59 | 4.72 |
| MICH | CERN | 59.87 |
| CERN | MAX | 56.39 | 4.60 |
| MAX | CERN | 51.79 |
| UCSD | FIU | 46.08 | 4.52 |
| FIU | UCSD | 50.60 |
| UCSD | MASS | 42.43 | 4.45 |
| MASS | UCSD | 37.98 |
| UCSD | CLEM | 39.28 | 2.07 |
| CLEM | UCSD | 37.21 |
| MICH | UTAH | 18.66 | 0.18 |
| UTAH | MICH | 18.48 |
| STAR | UTAH | 16.05 | 0.16 |
| UTAH | STAR | 15.89 |
| MAX | UTAH | 24.52 | 0.15 |
| UTAH | MAX | 24.37 |
| NCSA | UTAH | 17.26 | 0.15 |
| UTAH | NCSA | 17.11 |
| MASS | UTAH | 29.34 | 0.14 |
| UTAH | MASS | 29.2 |
| MAX | STAR | 8.96 | 0.06 |
| STAR | MAX | 9.02 |
| MASS | MICH | 16.38 | 0.04 |
| MICH | MASS | 16.42 |
| MAX | MICH | 11.66 | 0.04 |
| MICH | MAX | 11.62 |
| MICH | NCSA | 4.33 | 0.03 |
| NCSA | MICH | 4.3 |
| MICH | STAR | 3.12 | 0.03 |
| STAR | MICH | 3.09 |
| MASS | STAR | 13.79 | 0.02 |
| STAR | MASS | 13.81 |
| STAR | CLEM | 15.73 | 0.01 |
| CLEM | STAR | 15.74 |
| MASS | MAX | 8.18 | 0.01 |
| MAX | MASS | 8.17 |
| MAX | NCSA | 10.18 | 0.01 |
| NCSA | MAX | 10.19 |
| NCSA | STAR | 1.71 | 0.01 |
| STAR | NCSA | 1.72 |
| MASS | NCSA | 15.01 | 0.00 |
| NCSA | MASS | 15.01 |

Table 1: OWL values in ms between selected pairs of nodes

We are going to use the data in Table 1 to identify pairs of nodes with a significant difference in one-way- latencies. This is a good indicator of routing asymmetry when the measurement methodology is the same for forward and reverse paths and readings are taken at about the same time. There can also be difference in latencies due to other factors like network congestion and varying routing protocols and hence we cannot conclude that the paths are asymmetric if there is a significant difference in one-way latencies. Using traceroute to identify the forward and reverse paths and finding differences in the entities of the path is a conclusive way of determining asymmetry within the network [3].

We try the traceroute command between the nodes mentioned in Table 1 to find out the hops and intermediate IP addresses. The traceroute from STAR to CERN is given in Table 2 and traceroute from CERN to STAR is given in Table 3. Traceroute for all pairs of nodes in Table 1 have been done and we try to identify the asymmetric paths.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Hop | IP Address | Latency 1 (ms) | Latency 2 (ms) | Latency 3 (ms) |
| 1 | 10.129.139.1 | 0.303 | 0.294 | 0.297 |
| 2 | 10.129.128.150 | 14.463 | 14.469 | 14.480 |
| 3 | 10.133.0.198 | 112.011 | 112.031 | 112.083 |
| 4 | 10.143.6.2 | 113.318 | 113.329 | 102.892 |

Table 2: Traceroute from STAR to CERN

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Hop | IP Address | Latency 1 (ms) | Latency 2 (ms) | Latency 3 (ms) |
| 1 | 10.143.6.1 | 0.505 | 0.499 | 0.525 |
| 2 | 10.133.0.185 | 97.790 | 97.799 | - |
| 2 | 10.133.0.197 | - | - | 109.202 |
| 3 | 10.129.128.149 | 113.538 | 103.843 | 103.868 |
| 4 | 10.129.139.2 | 101.849 | 101.834 | 103.580 |

Table 3: Traceroute from CERN to STAR

A total of 10 runs of traceroute was performed between each pairs of nodes resulting in 10 routes in each direction for the pair of nodes. The node pairs displaying consistent route deviations across the majority of runs were identified as exhibiting asymmetry. To ascertain the precise path between nodes in instances of identified asymmetry, the mode, representing the most frequently occurring path among such instances, was selected. These selected paths were used for calculating Absolute and Normalized Asymmetry between pairs of nodes.

Now we try to quantify the asymmetry in the paths making use of Absolute and Normalized Asymmetry mentioned in the research section of this project. The level of asymmetry between each pair of nodes mentioned in Table 1 was calculated.

# Results and Analysis

From Table 2 and Table 3 we can see that the forward path from STAR to CERN and the reverse path from CERN to STAR are different. We can see the 2 routers (both mentioned as Hop 2) which are visible after the first hop from CERN to STAR. This shows that the router (10.133.0.197) which was part of the forward path is present in the network but this time the packet was routed through a different router (10.133.0.185) which also showed lower latency values.

Traceroute performed on the other pairs of nodes showed that there was asymmetry between UTAH and CERN, and MASS and CERN. With the significant OWL differences between CLEM and CERN (10 ms), we would think that this path also exhibits asymmetry, but it was not the case. The path between CLEM and CERN was symmetric during the experiment. This shows that although OWL is a good indicator of asymmetry in the network, it is not conclusive. An observation made from the experiment was that we found asymmetrical paths between nodes only in cases where the difference in one-way latencies between the nodes was more than 2ms. From conducting traceroute on other nodes, we found that the pair of nodes (MASS, UCSD), (UCSD, FIU) and (UCSD, CLEM) all had asymmetrical paths between them. This points out to us that CERN and UCSD are more susceptible to having asymmetrical paths than the other 8 nodes which were considered as part of the experiment.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Node pairs | A A | N A | length(u) | length(v) | length(u)+length(v) |
| CERN, UTAH | 2 | 0.2 | 5 | 5 | 10 |
| CERN, MASS | 2 | 0.33 | 3 | 3 | 6 |
| CERN, STAR | 2 | 0.33 | 3 | 3 | 6 |
| UCSD, MASS | 4 | 0.33 | 6 | 6 | 12 |
| UCSD, FIU | 8 | 0.66 | 6 | 6 | 12 |
| UCSD, CLEM | 4 | 0.33 | 6 | 6 | 12 |

Table 4: OWL values in ms between selected pairs of nodes

Table 4 shows absolute and normalized asymmetry between pairs of nodes. Out of the 45 pairs of nodes taken for this experiment, 6 had asymmetry between them. This shows 13.33% of the paths were asymmetric in this case which is a similar value to the percentage of asymmetric paths in a network found as 14% in [2]. We can see that the path between UCSD and FIU has the highest value of Normalized Asymmetry showing us that this is the most asymmetric path between the nodes taken for the experiment.

# Conclusion

This study investigates routing asymmetry in the FABRIC testbed utilizing Precision Time Protocol for one-way latency measurement and traceroute for path analysis. We then quantify this asymmetry and try to find the paths that are more asymmetric than the others. The results of the experiment reveal distinct asymmetrical routes between specific node pairs highlighting the complexity of network routing which is desirable in certain conditions like congestion control. While asymmetry was anticipated based on latency differences, traceroute analysis which checked the entities along the path provided conclusive evidence to asymmetric paths and the normalized asymmetry values provided the extent of asymmetry.

One-way latencies can also serve as indicators of network congestion. Protocols can utilize latency measurements to implement congestion control mechanisms, such as adjusting transmission rates or routing paths to alleviate congestion and prevent packet loss. Insights derived from one-way latency analysis can shape the development and refinement of protocols over time. By incorporating latency-related feedback into protocol design processes, developers can iteratively improve protocol performance and adaptability.

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