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Multi-Path Forwarding Strategy for Named Data Networking Based on Pending Interests and Available Bandwidth

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***Abstract*—Named Data Networking (NDN) is a new Internet architecture, and it focuses on the content or name rather than the location or address. One-to-many communication has become the main feature of NDN networks. Therefore, forwarding strategy plays an important role in the content delivery performance enhancement of NDN networks. Most existing schemes tend to consider one or two metrics of different faces, such as round trip time(RTT), pending Interests (PI) and bandwidth (BW). Such single-metric or dual-metric designs usually lower accuracy in characterizing path performance. In addition, the Data packet can carry rich performance information of the path it passes through, which is more powerful than estimating the path performance on the local interface. To this end, we propose a multi-path forwarding strategy named PIBW, considering multiple metrics including PI, available BW, etc. We implement PIBW and conduct performance evaluations based on ndnSIM. Simulation evaluation shows that PIBW outperforms baseline solutions in terms of throughput, link bandwidth utilization and convergence time.**

***Index Terms*—Named Data Networking, multi-path forwarding, load balance, pending interests, available bandwidth.**

I. Introduction

Named Data Networking (NDN) [1] is a novel network architecture. Ambitioning a shift from location-centric to content-oriented networking, NDN is intended to transcend the limits of current TCP/IP architecture in content distribution and retrieval. Generally, there are two kinds of packets transmitted over NDN networks, namely Interest and Data, which contain requests and contents, respectively. Interests are expressed by consumers for specific content from the network, and the corresponding Data will be provided by producers or routers with caches. Alongside with the content producers, the ubiquitously existing caches are also allowed in NDN networks to act as content providers, which enables multi-source multi-path transmission towards an enhanced content dissemination efficiency and security. In the field of NDN, it has become a key challenge and emerging research topic to design appropriate mechanisms for supporting efficient multi-path forwarding. This is critical to the various applications such as tele-health and intelligent transportation systems [2], [3].

As a pioneering solution, the adaptive forwarding [4] has become a baseline design since its emergence. With adaptive forwarding, every NDN router maintains three tables: the Pending Interest Table (PIT) that lists all forwarded pending Interest packets that have not received corresponding Data, as well as arrival and departure information, the Forwarding Information Base (FIB) that provides the next hop interface(s) for each prefix, and the Content Store (CS) that records all Data packets cached by the local router. Upon every arrival of Interest packet, the router queries corresponding information from all three tables, so as to be capable of monitoring the network status in real time, and therewith making intelligent forwarding decisions for a better transmission performance than those of traditional routing solutions.

Within that framework, several forwarding strategies have been proposed in the past years, such as the weighted round-robin with various weight functions [5] [6], and the Fast Pipeline Filling (FPF) [7] that pursues a possibly fastest filling of the link bandwidth. Despite of the efforts, existing strategies generally aim at some certain optimization goal or application scenario, and therefore consider single or two metrics, which cannot comprehensively reflect the performance of every path. Complex, high-dimensional multivariate models are therefore usually required to estimate the path performance. Additionally, existing strategies commonly depend on some parameters, such as FPF needs to know the accurate path capacity in advance, which is impractical.

In addition, in recent years, technologies such as P4 [8], SDN [9], and In-band Network Telemetry (INT) [10], have been proposed on the traditional IP network architecture. In essence, they make IP network devices more intelligent, so as to achieve more fine-grained and intelligent sensing and

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control in the process of data packet forwarding [11], [12]. Different QoS and QoE objectives will be easily achieved [13], such as deterministic delay, etc. For example, HPCC congestion control algorithm [14] introduced INT into the Data Center network to achieve the goal of high bandwidth, low delay, stability and security. With INT, fine-grained information on the transmission path is obtained, including link capacity, link load, queue length, time stamp and the number of bytes transmitted, and then the accurate congestion window is calculated according to these information to achieve congestion control. In order to achieve near-zero queue, HPCC controls the congestion window at the source side near the target value where the link bandwidth utilization is lower than 100 percent. Although INT technology has not been applied to NDN networks, the stateful forwarding plane of NDN network has the potential of fine-grained network state awareness and intelligent control. For example, in addition to maintaining real-time packet forwarding information in the PIT, NDN network devices can also obtain information such as queue length, outInterest, and inData of each interface (for each perfix), so they have better capabilities than INT. Therefore, it has great potential to adopt INT in NDN network architecture.

In this work, we aim to maximize the end-user throughput and link utilization of each path, without requiring priori knowledge about pipeline capacity or available bandwidth. To achieve this, we combine three metrics to implement a multi-objective face selection. The key contributions of this paper are as follows:

- We introduce the technology similar to INT into NDN architecture, and each node obtain more performance information of upstream paths for forwarding decision of interests.
- We propose a multipath forwarding strategy, which considers the residual capacity, RTT and available bandwidth of the upstream path, and does not need a priori link information.
- We consider the available bandwidth of the upstream path to avoid the impact of local single link congestion on the global network performance.

The remainder of this paper is organized as follows: We start with Sec. II that gives a brief review to existing works related to this study, then in Sec. III we interpret the design rationale of our proposal. In Sec. IV we implement our design and compare it with the existing work, and we conclude this paper in Sec. V.

II. Background

A. NDN Architecture

With the significant developments in computer and Internet technology, cloud computing [15], big data, and machine learning [16], the demand for fast and securely transferring and processing of large amounts of data becomes critical to our society. Named Data Networking [1] is a novel network architecture compared with current TCP/IP architecture. NDN aims to implement a shift from location-centric to content-oriented, designed to improve content distribution and retrieval. NDN network transmits two formats of packets, Interest and Data, i.e., the request and content. Due to the existence of ubiquitous cache in NDN, both caches and content producer can act as content providers, which makes multi-source multi-path transmission possible to improve content dissemination efficiency. As a result, multi-path forwarding has become an important research issue in NDN networks. The corresponding forwarding mechanism needs to be studied to support efficient multi-path forwarding.

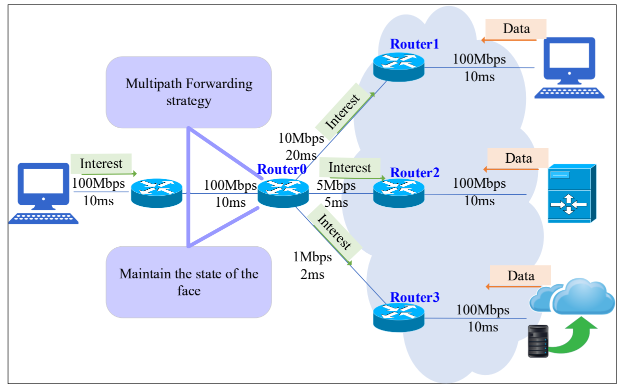

Fig. 1: Network topology.

B. NDN Forwarding Model and Opportunities

The Interest packet and the Data packet are one-to-one relationship. The forwarding paths of Interest and Data with the same name are the same path, but the directions are opposite. According to the forwarding decision, the forwarding node selects the next hop to forward the received Interest packet, and records the interfaces where the Interest packet arrives and leaves in the PIT table. The corresponding Data packet traces the path of the Interest packet according to the PIT entry, so as to satisfy the downstream request nodes [17] [18].

According to the current implementation of NDN architecture, such as ndnSIM [19] [20] [21] and NFD [22], there are some tag fields in the Data packet, so the Data packet can record the performance information of the path to downstream nodes, which is similar to INT. Therefore, the downstream nodes can perceive multi-dimensional performance metric of upstream paths instead of the single Round-Trip Time (RTT) metric. Therefore, forwarding nodes are able to make real-time forwarding decisions with more network information, such as available bandwidth, RTT, link load, the queue length, the packet queueing delay, the number of hops, the provider and even the number of flows and caching information.

C. Multipath Forwarding

Detti et al. have discussed in [7] five multi-path forwarding strategies with different goals: Pending Interest Equalization (PE) that aims to keep the number of pending Interests in equality of different faces, Round Trip Time

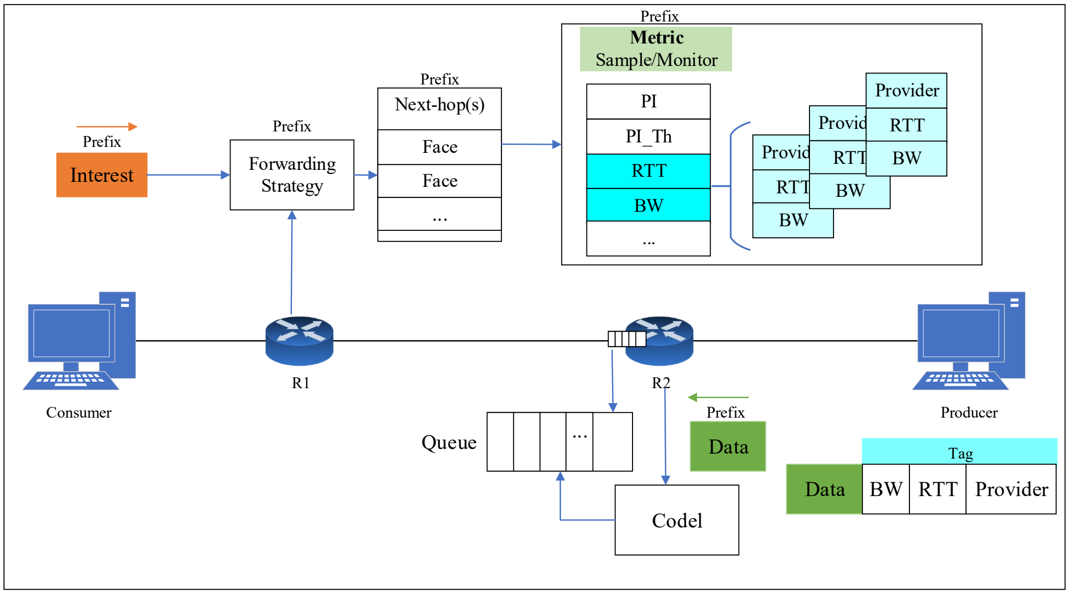

Fig. 2: PIBW Design

Equalization (RE) that aims to equalize the RTT of different faces, FPF that tends to fill the link bandwidth as fast as possible, in addition to the strategies of UG [5] and CF [6], which both use weighted round-robin to distribute the incoming Interests, with the weights inversely proportional to the RTT and Pending Interest (PI), respectively. However, each of them is associated with some identified drawback: PE works well only in the ideal scenario, where all available paths share the same bandwidth and RTT. RE suffers from premature convergence at low bandwidth utilization or suboptimal forwarding ratio, due to the heterogeneous RTT of different faces. FPF is limited by its requirement of the knowledge about pipeline capacity; both UG and CF consider only a single metric that cannot accurately reflect the path performance.

Schneider et al. proposed a practical congestion control scheme called PCON [23], which also includes multipath forwarding component. It focuses on adjusting the traffic split ratio to shift traffic from congested faces to alternatives, so as to maximize the end-user throughput while minimize the network cost (path length). To achieve this goal, PCON maintains a forwarding percentage for each face with fwPerc(F) and adjusts it according to the marked Data from upstreams. In addition, PCON adjusts the forwarding ratio among faces w.r.t. several parameters such as the distance (hop count) to congested link, which critically determines its converging performance. However, the challenge of parameter optimization has not been resolved.

Ren et al. reported a dynamic multi-path forwarding strategy called DMF [24]. Under the assumption that each $face_i$ knows its BDP ($BDP_i = (BW_i \times RTT_i)/S_D$) of associated path in advance, DMF adopts RTT and available bandwidth as its metrics at the initial and saturated phases, respectively, to achieve the goal of making full use of multiple available paths for improving the receiving rate of consumers. However, the deployment of BDP is challenged in practice by the estimation of available bandwidth BW_i.

There have also been other adaptive forwarding strategies presented for different goals, such as the SAF (Stochastic Adaptive Forwarding) [25] for maximizing the Interest satisfaction ratio. In [26], authors design and implement forwarding strategy based on the adaptive smoothed RTT, called ASF.Generally, for every certain optimization goal, a specific multi-path strategy should be designed separately.

III. PIBW Design

A. Scheme Overview

For each incoming Interest, PIBW forwards it based on the residual or available PI and RTT. For each received Data that marked with congestion signal, PIBW adjusts the PI threshold based on the congestion marking from upstream nodes. Here, we use the congestion marking method as Codel [27] and implementation as PCON.

The process of Interest forwarding exploiting PIBW is as follows. As shown in Fig. 1, PIBW is implemented on Router0, and there are three next hops to forward Interest to retrieve Data. PIBW maintains PI, PI threshold (the path capacity), RTT, and available bandwidth for each face. For each received Interest, PIBW selects the face with the largest available or remaining capacity $(1 - PI_{fi}/PI\_Th_{fi})_{max}$, meanwhile its PI_{fi} does not exceed its threshold $/PI\_Th_{fi}$. If all the $(1 - PI_{fi}/PI\_Th_{fi})$ are equal, PIBW selects the face with RTT_{min}. If all faces' PI exceed their PI threshold, the Interest packet will be delayed. The PI_Th_{fi} is adaptively updated based on the congestion marks received from the corresponding upstream.

Algorithm 1 PIBW Multi-path Forwarding Algorithm

```
Receive an Interest message;
Forwarding Interest to RankedFace(1);
if Recevie Data D1 with Congestion Mark from Face i then
    PI_Th(i) = PI(i);
    if PI_remain(all) > 0 then
        D1.Mark(0); // set the congestion mark to 0;
else
    Forwarding D1 to Downstream nodes;
```

Algorithm 2 PIBW FaceList Update Algorithm

Input: $FaceList$, $Face(i) \in FaceList$ and i = 1,2,3,...,N, $PI(i) = OutInterest(i) - InData(i)$, $PI\_remain(i) = 1 - PI(i)/PI\_Th(i)$ and the initial $\{PI(i), PI\_remain(i), PI\_Th(i)\}$ is $\{0, 1, 200\}$.

Output: $set : RankedFace$

```
RankedFace{i} = FaceList{i}, i = 1,...,N;
for i = 2; i ≤ N do
    RankedFace.insert(i);
function FaceCompare:
if PI_remain(i) > PI_remain(i − 1)&&PI(i) < PI_Th(i) then
    return true;
else if PI_remain(i) == PI_remain(i − 1)&&PI(i) < PI_Th(i)&&PI(i − 1) < PI_Th(i − 1) then
    return(Rtt(i) < Rtt(i − 1));
else
    return false;
for I = 2; i ≤ N do
    if PI(i) > PI_Th(i) then
        RankedFace.earse(i);
```

PIBW exploits the same congestion detection and notification method as PCON, which uses an AQM mechanism called CoDel [27]. CoDel measures each packet's queuing delay on the outgoing face, if the time exceeds a threshold (100ms), the packet will be marked to notify the congestion to downstream nodes. CoDel detects congestion at the location where congestion occurs, so it is more accurate.

The Interest processing of PIBW is described as Algorithm.1.

B. Available Capacity and RTT-based Forwarding

PIBW uses PI and PI_Th to control available capacity. RTT is calculated by subtracting the receiving time of the Data and the sending time of the Interest. Interest forwarding essentially selects the most suitable face from the available faces (next hops) provided by the corresponding FIB entry, and PIBW maintains a rank list of faces (RankedFace) for each prefix. The RankedFace is shown as follows and all the parameters are readily available. The RankedFace updating algorithm is presented in Algorithm.2. The data structure RankedFace we implement is extended on the basis of ASF [26], and We consider and design the new relevant metric and sorting algorithm(FaceCompare) in ndnSIM. PIBW uses the basic RTT of each face, and the RTT is the cumulative sum of the link delay on the path which the Data packet returns, excluding queue delay.

$< 1 - PI_{f1}/PI\_Th_{f1}, RTT_{f1} >$,
$< 1 - PI_{f2}/PI\_Th_{f2}, RTT_{f2} >$,
$< 1 - PI_{f3}/PI\_Th_{f3}, RTT_{f3} >$,

where,

1) $PI_{fi} \leq /PI\_Th_{fi}$,
2) $1 - PI_{fi}/PI\_Th_{fi} \geq 1 - PI_{fi+1}/PI\_Th_{fi+1}$,
3) $RTT_{fi} \leq RTT_{fi+1}$, when $1 - PI_{fi}/PI\_Th_{fi} = 1 - PI_{fi+1}/PI\_Th_{fi+1}$

C. Initial Available Capacity Setting

The capacity threshold is a value that needs to be optimized related to the maximum path capacity, traffic load and optimization goal. It is a dynamic value. Therefore, we need to set the initial value of the capacity threshold, here, we set it to 200. Our principle is to set the threshold as large as possible, because our work is based on PCON, and its congestion marking mechanism will eventually make the capacity threshold and the PI value converge to a equilibrium point. In addition, assuming that the capacity threshold is set correctly in advance, this method can quickly converge to the equilibrium point. We leave the solution of optimal value capacity in future work.

PIBW prioritizes the remaining PI to ensure that all paths or faces are enabled during the start-up phase of the flow, not just a single path or face of minimum RTT.

D. Available Bandwidth Monitoring and notification

We exploit the congestion marking method described by PCON [23]. Therefore, each face may receive a Data packet carrying a congestion mark from its corresponding upstream. However, if one face receives a Data packet with the congested mark, it does not mean that other faces are also congested. In this case, the congestion mark should not be feed back to the downstream nodes or consumers. In order to correctly respond to congestion signals from upstream nodes, this strategy periodically monitors the available bandwidth of each face. The available bandwidth of each $face_i$ is represented by $availBW_i$, which is calculated from the available bandwidth and traffic load of the corresponding upstream link, $availBW_i = BW_i - Load_i$. BW is the physical bandwidth of the upstream pipeline. $Load_i = onBytes_i/T$, and T is the period of monitoring the $onBytes_i$, and $onBytes_i$ is the received bytes of $face_i$. In this way, the available bandwidth of each face is known. $availBW_i$ is maintained on each face. The Data packet updates its BW tag and returns the minimum BW to downstream faces. As is shown in Fig. 2.

Available bandwidth monitoring: To feedback the upstream congestion information, the available bandwidth shall be monitored as reference. However, we do not necessarily require its accurate value, but only to know if it is zero. Other available bandwidth estimation methods based on delay or loss can also be used to obtain more accurate bandwidth, such as packet-pair or Probe Rate Model (PRM) [28] [29] [30], and so as to calculate the available bandwidth in real time, and then obtain the PI threshold.

The available bandwidth is very important to the dynamic adjustment of PI threshold, especially to the increase of PI threshold.

Available bandwidth notification: Every Data uses its tag field to carry and return the information of path that it passes [31]. Such information, including the available bandwidth, the RTT, and the corresponding provider, are measured and written into Data by upstream nodes, and consumed by downstream nodes to optimize their multi-forwarding decisions. This mechanism is similar to the In-band Network Telemetry function of NDN, which enables the nodes to optimize the forwarding control model or algorithm.

E. React to the Received Congestion Mark

If $face_i$ receives a congestion mark, its PI threshold needs to be adjusted. Besides, the strategy needs to decide whether to continue to pass the congestion mark to downstream nodes. Both designs are detailed below.

Decrease the capacity threshold: we set the PI threshold PI_Th_{fi} to the current PI_{fi}. Because PCON assumes that the buffer queue capacity is unlimited, it can tolerate a large PI threshold estimate. If the PI threshold estimate is too small, it will not cause negative effects.

Whether to forward the congestion mark to downstream: a face receiving a congestion mark does not necessarily have to notify downstream nodes or consumers. In this design, whether to continue to pass the congestion mark to the downstream nodes or consumers depends on the available bandwidth of other faces. When $face_i$ receives a Data packet with a congestion mark, it checks whether the sum of the available bandwidth of other faces except $face_i$ is greater than 0. If it is greater than 0, erase the congestion mark, otherwise, continue to pass the congestion mark to downstream nodes.

IV. EVALUATION

To evaluate the performance of PIBW, we compare it with several related works. As mentioned in [32], different forwarding strategies have different objectives, and we try to compare PIBW to forwarding strategies with similar objectives. We use PCON to detect and mark congestion, and also the consumer. We conduct simulations based on Random load balancer, for PI, FPF, Weight, PIBW. The detailed description of these strategies and the related configurations we use are as follows. The combination of consumers and forwarding strategies are: PCON+Random, PCON+PI, PCON+Weight, PCON+PIBW, PCON+FPF.

Random load balance: this strategy is present in ndnSIM simulation, the principle is that for each received Interest, the strategy randomly selects a face based on the corresponding FIB entry to forward.

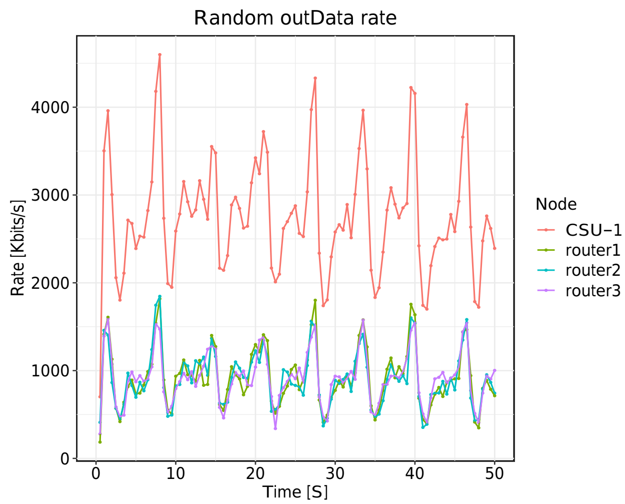

Fig. 3: Random Strategy: Consumer Receive-Rate or Throughput, and Rate of each path (OutData rate).

PI: PI strategy is a simple adaptive and stateful forwarding strategy, which maintains the number of Pending Interest for each face. The goal of PI strategy is equalizing the PI of each face regardless of other parameters such as RTT or capacity. However, this is the simplest strategy to implement.

FPF: the rationale of FPF is to fill the pipeline as quickly as possible to maximize the receive-rate. The challenge is that the strategy assumes a-priori knowledge of the pipe capacity for each face. Here, we assume that the FPF knows the pipeline capacity through probing, so some probing overhead is required. In addition, Data payload size is set as 1024 bytes. Since we use Wireshark [33] to capture its Frame and observe 1114 bytes on wire, the overhead of NDN and Underlying protocols is around 90 bytes. The payload size and overhead affect the calculation of pipeline capacity. Because we use PCON for congestion detection and marking, the principle of setting this value of C is to ensure C is between the delay bandwidth product and the congestion mark threshold.

$C_i = 2 \cdot R_i \cdot D_i(BDP_i : Mbits) + L_i(buffer : packets)$, therefore,

$C_1 = 2 \cdot 10Mbps \cdot 20ms + L_1 = 44 + L_1 = 78$,

$C_2 = 2 \cdot 5Mbps \cdot 5ms + L_2 = 5 + L_2 = 34$,

$C_3 = 2 \cdot 1Mbps \cdot 2ms + L_3 = 0 + L_3 = 29$.

Weight: this strategy sets a weight for each face to forward each received Interest. Therefore, the performance of the forwarding strategy depends on the weight of each face. UG proposed in [5] sets the weight of each face to be inversely proportional to its RTT. In our simulation, we set the weight of each face to be proportional to delay bandwidth product, and it can obtain more stable and better performance. This strategy requires a-priori knowledge of delay bandwidth product and this value is difficult to obtain accurately. We use it as one baseline, therefore, we show the results with settings achieving good performance.

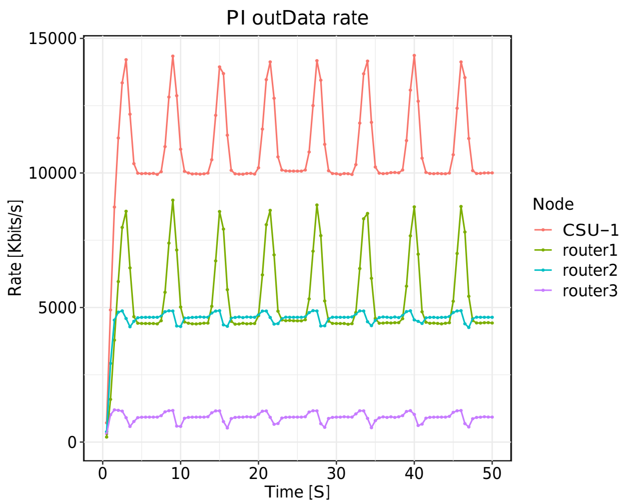

Fig. 4: PI Strategy: Consumer Receive-Rate or Throughput, and Rate of each path (OutData rate).

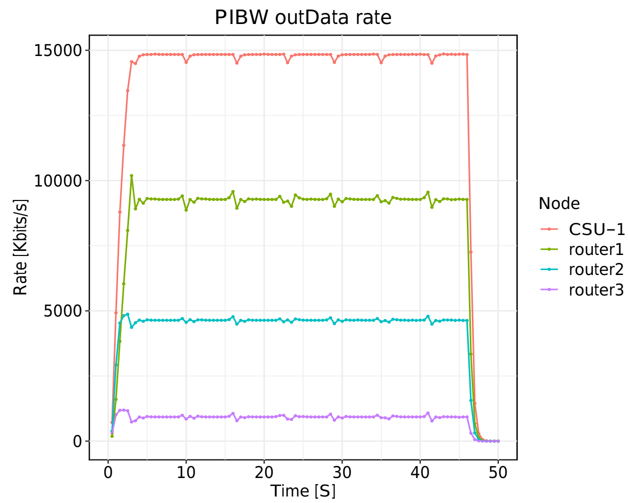

Fig. 6: PIBW Strategy: Consumer Receive-Rate or Throughput, and Rate of each path (OutData rate).

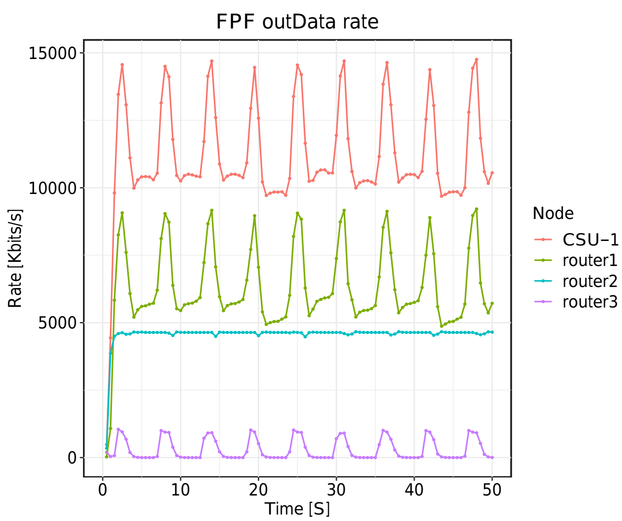

Fig. 5: FPF Strategy: Consumer Receive-Rate or Throughput, and Rate of each path (OutData rate).

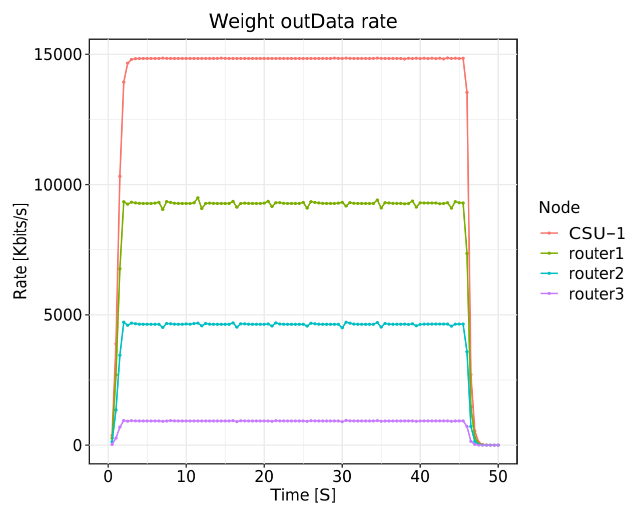

Fig. 7: Weight Strategy: Consumer Receive-Rate or Throughput, and Rate of each path (OutData rate).

The network topology is shown as Fig. 1. The delay and bandwidth of the three paths are different. The queue size is large enough to use CoDel. The consumer exploits PCON, and the window increase and decrease using Additive Increase Multiplicative Decrease (AIMD).

Fig. 3 $\sim$ Fig. 6 illustrate the performance of different strategies in terms of receive-rate (throughput) and link bandwidth utilization. From Fig.3 $\sim$ Fig.6, we can observe $PIBW > FPF > PI > Random$. Random performs poorly compared with other strategies because it selects next face randomly. FPF is better than PI because of a PI threshold (capacity) is used to limit the PI of each face. Although FPF sets a capacity threshold for each face, when the PI value of all faces exceeds this threshold, FPF discards the Interest packet, therefore it impacts the performance.

As shown in Fig. 7, weight strategy performs the best compared with the former four strategies, because weight strategy sets the ratio of different faces. The most important is that it is no need to discard Interest packets like FPF because there are no unqualified faces.

The performance of PIBW is very close to that of weight. Since the ratio of different faces is difficult to pre-set, PIBW performs the best.however, if the Data packet carries the exact value of available bandwidth and RTT of upstream, weight strategy performs best. In this work, we also optimize the overhead of Data tag for weight strategy in the implementation, and it is also a small contribution point.

V. Conclusion

As an inherent characteristic of NDN, mult-path forwarding has a prominent impact on the content delivery performance.In this paper, we systematically analyzed the pros and cons of existing solutions, and proposed an adaptive multi-path forwarding strategy called PIBW, which relies on fewer parameters and exploits the congestion marking method adopted by PCON to maximize the receiving rate or throughput. The proposed method PIBW tends to make full use of the available bandwidth, and introduces a real-time bandwidth estimation mechanism to eliminate the impact of a single path congestion signal on the overall transmission. Simulation results demonstrated that PIBW outperformed existing NDN multi-path forwarding strategies in terms of both throughput and link bandwidth utilization.

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