HLAF: Heterogeneous-Latency Adaptive Forwarding Strategy for Peer-Assisted Video Streaming in NDN

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***Abstract*—Named Data Networking (NDN) is a promising Future Internet architecture to support content distribution effectively. Specifically, P2P may gain benefits from NDN, as NDN inherently provides a flexible forwarding plane for multi-source and multi-path communications. Extensive studies have been proposed for multi-path and multi-source communications. However, these approaches are heavily affected by link latency, which leads to illogical resource allocation and low link utilization for P2P. This paper proposes a new Heterogeneous-Latency Adaptive Forwarding (HLAF) strategy for peer-assisted video streaming in NDN. In peer-assisted video streaming, users (peers) proactively share the available content to others. By measuring the performance of forwarding interfaces, using both the level of congestion and the round-trip time, HLAF enables efficient P2P communication, which minimizes the latency and enhances the throughput. The experimental results show that the proposed strategy can enhance the peers' and Quality of Experience (QoE).**

Keywords — Peer-to-Peer; Named Data Networking; Multipath Forwarding;Video Streaming

I. INTRODUCTION

A recent study carried out by [1] indicates that almost 70% of the Internet usage in North America was held by real-time entertainment content, while video services (e.g. provided by Netflix and YouTube) accounted for more than 50% at peak periods. Popular content that is downloaded repeatedly places significant demands on network infrastructures. As most networking requests from users are aimed to retrieve content, regardless of the storage location, Named Data Networking (NDN) [2] is proposed to remodel data acquisition by linking users to content directly. Particularly, the address identifier is replaced by Unified Resources Identifier (URI) - name. In NDN, consumers[1] send interest packets with a name for retrieving data packets from any producer[2] within the network. If interest packets with an identical name are forwarded to the same router within a short time interval, they are aggregated [2]. After the data packet is retrieved, the pending interests with the name of the data packet are satisfied. The data packet is then returned to all consumers requesting the content.

Somewhat like Content Distribution Networks (CDN) [3], NDN distributes content to the infrastructure along the forwarding path. Consumers can then retrieve the content from this infrastructure directly without accessing the original server. However, unlike CDN, the infrastructure in NDN typically consists of dispersed routers with limited caching ability, which exacerbates the management problem. By mean of empirical evaluations, a recent study [4] suggests deploying a large amount of memory at the edge nodes to maximize the cache utilization and reduce management overhead. Without intra-network caching and using the client-server model, the resources of intra-network facilities can be insufficiently utilized. In contrast, employing the Peer-to-Peer (P2P) model, which enables consumers to share content with each other, can further improve the resource utilization.

The studies using P2P in NDN can be broadly categorized into two classes [5], namely, mediator and clean-slate. The mediator approach makes NDN/ICN deliver the P2P messages, where the name URI is appended to the peer identifier (e.g. /video1/s1 → /peerID/video1/s1) [5]. The name URI of the same content will become different after appending the identifiers. This change causes difficulty with interest aggregation and content caching, unless the router is designed to remove the identifier from the name. However, this approach is against the principle of information-centric networking. In contrast, the clean-slate approach makes P2P operate directly in NDN/ICN [5], which enables consumers acting like servers which publish the availability of content for other consumers to download. This approach does not require the routers to process the name as in the mediator approach but requires re-developing P2P applications [5] and implementation of robust forwarding strategies for multipath communication.

Current studies of P2P in NDN are mainly concerned with the application development without a thorough consideration of forwarding and traffic control strategies. As the uploading abilities of different peers can be distinct and mutative, it is essential to balance the requests flowing to the peers. Existing adaptive forwarding strategies are heavily affected by link latency, which is not considered a proper metric for P2P communications and cannot detect the failure/rejection at the peers' side. In this paper, we propose a new Heterogeneous-Latency Adaptive Forwarding Strategy (HLAF) for clean-slate P2P in NDN. HLAF is able to

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[1] Consumer denotes the user downloading content

[2] Producer denotes the node providing content

combine two metrics (congestion-level and RTT) for forwarding decisions, which efficiently support content sharing among peers with minimum latency and maximum throughput. Experimental results show that peer-assisted video streaming when is implemented with HLAF can significantly enhance peers' Quality of Experience (QoE) in terms of reducing video playback stalling time and improving video playback qualities.

To the best of authors' knowledge, the main contributions of this paper are:

- An introduction to a practical clean-slate design – Peer-Assisted Video Streaming in NDN.
- A new HLAF strategy to hybrid the RTT and congestion-level metrics for efficient support content distribution on heterogeneous-latency peers and servers.
- An evaluation and discussion of the video transmission performance of the proposed HLAF with conventional forwarding strategies.

This paper is organized as follows: Section II presents an overview of peer-assisted video streaming in NDN. The detailed design of the heterogeneous-latency adaptive forwarding strategy is presented in Section III. Section IV evaluates the performance of HLAF on peer-assisted video streaming. Related works are presented in Section V. Section VI draws a conclusion from work presented.

II. PEER-ASSISTED VIDEO STREAMING IN NDN

In this section, we first revisit the basic concept of a pull-based video streaming in NDN. Then, a practical design is proposed to support the efficient P2P communication for video streaming.

A. *Video Streaming in NDN*

As several elements (such as pull-based communication; content dealt within chunks) in NDN and Dynamic Adaptive Streaming over HTTP (DASH) are mutually congenial [6], the application scenario discussed in this paper focuses on delivering video under the DASH framework in NDN. First, an entire video is divided into several segments with equal playback time (e.g. 2s). Then, each segment is encoded into different representations (i.e. chunks) with different qualities (e.g. codec: MPEG-4, bitrate: 354kbps, 622kbps, 1283kbps and etc.). In order to deliver chunks over NDN efficiently, the chunks are split into slices with the size of Maximum Transmission Unit (MTU). As consumers lack the information of chunk size and do not know how many slices should be downloaded for a chunk, a manifest packet is initially retrieved to indicate a number of slices in a chunk.

Each chunk within a video is named as a hierarchical structure: /video_name/codec_id/seqqua, where *seq* denotes the time index of the chunk and *qua* reflects the quality of the chunk. The users first download the "Media Presentation Decryption (MPD)" file to get the overview (e.g. quality, bitrate, filename and sequence number) of a video. According to the load of the network (e.g. bandwidth), users select a suitable video chunk based on the conventional window-based adaptation logic [7].

B. *Video Streaming over P2P in NDN*

Traditional host-centric P2P applications (e.g. over TCP/IP) enable peers to communicate with other peers directly. However, the routers are not responsible for discovering peers or balancing the load. By removing the host information in NDN, consumers are not designed to directly communicate to producers. Instead, routers are responsible for balancing the traffic to peers or servers. Thus, the peer selection in traditional P2P is mapped to content publishing and adaptive forwarding in NDN.

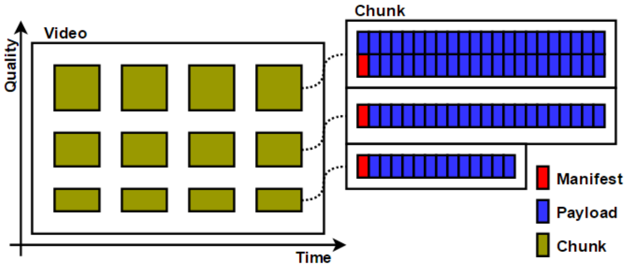

Figure 1 Composition of a DASH video

After a chunk is fully downloaded, the peer publishes its name to the network and waits for the routers to update forwarding tables. Notice that, the chunk-level publication via strings can lead to significant overhead, as a video may have thousands of chunks. In this respective, bitfield [8] is introduced in order to exchange information between nodes. For instance, the consumer would like to publish the chunks /Rocky/MPEG4/$03$02, /Rocky/MPEG4/$03$01 and /Rocky/MPEG4/$02$01. The consumer will publish content as:

$$\text{/Rocky/MPEG4} \quad + \quad \begin{matrix} \overbrace{0b0100}^{\text{Quality 2}} \\ \underbrace{0b0110}_{\text{Quality 1}} \end{matrix}$$

Each binary reflects the availability of a specific chunk. For example, the binary of Quality 1 (0*b*0110) denotes the availability of chunks at time index 2 and 3. Instead of full-length strings, the overhead of the synchronizing bit-field is relatively small, as it only consists of a string prefix and several binaries.

By introducing the bit-field, the overhead of routing synchronization for each time is significantly reduced. However, if a peer continuously publishes content every time it finishes downloading a chunk, the synchronization overhead will still be large. The frequency that peers are allowed to publish content is a topic that requires further study.

III. HETEROGENEOUS-LATENCY ADAPTIVE FORWARDING

A. *Principle of HLAF*

Conventional forwarding strategies (e.g. [9], [10]) prefers to utilize the path that has a lower round-trip time (RTT)[3]. However, RTT is not a perfect metric to evaluate the performance of a path [11]. For a peer, nearby peers may have smaller latency but also less uploading ability compared to other peers and servers, therefore, solely using RTT is not reliable.

To this end, HLAF is a heuristic strategy which aims to minimize congestion while keeping RTT as low as possible. In practice, HLAF adjusts the forwarding allocation to interfaces based on the explicit congestion signals (NACK) and RTT[4] simultaneously.

The congestion is set to the prior metric while RTT is used as the auxiliary one. Because the congestion caused by inaccurate allocation reduces the total throughput and collapses network, it is always necessary to avoid congestion. Within the solution set that avoids congestion, HLAF further searches for the solution with the smallest latency.

B. *Congestion Detection and Notification*

Two types of NACK designs (i.e. data-based and interest-based) are mentioned in the literature to detect congestion and explicitly feedback signal. The data-based NACK proposed by Yi *et al.* [12] proactively checks the data queue length of the link layer. If the queue length exceeds a threshold, the router rejects forwarding any interests and returns NACK packets.

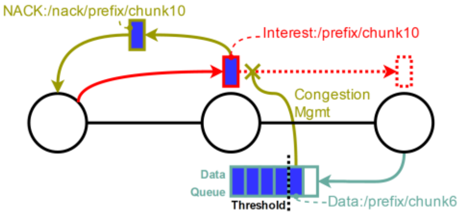

Figure 2 Data Based Congestion Detection

In contrast, Wang *et al.* [13] introduced Hop-by-hop Interest Shaping (HIS), which detects congestion by monitoring delayed interests. Normally, the tiny interest packets will block the network. In HIS, the router pre-calculates the interest forwarding rate of any interface, which avoids the congestion of returned data packets. The interest packets that exceed the forwarding rate are delayed in the interest queue, and then if the number of interests delayed in the queue exceeds the threshold, the router returns NACK packets upstream.

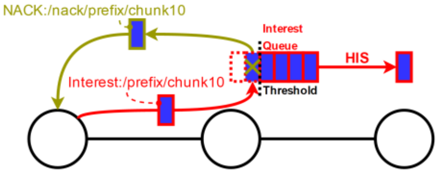

Figure 3 Interest Based Congestion Detection

In this paper, HIS is employed for congestion detection and notification as it provides two significant benefits as follows:

- ***Earlier Detection***: HIS always detects congestion earlier than the data-based approach [12], as the data-based one takes a longer time (more hops) to gather the congested returning data packets at the link layer than delaying the forwarding interest packets.
- ***Security***: The NACK packets generated by data congestion can be delayed in the queue. This may require message prioritization which opens to the security weaknesses [14]. In HIS, as link layer congestion is avoided, NACKs can be freely returned upstream without being prioritized.

C. *Operating Logic*

In order to achieve bi-metric (RTT and congestion level) allocation, HLAF makes interfaces maintain a congestion state (0: congestion-free and 1: congested) for different operations. In

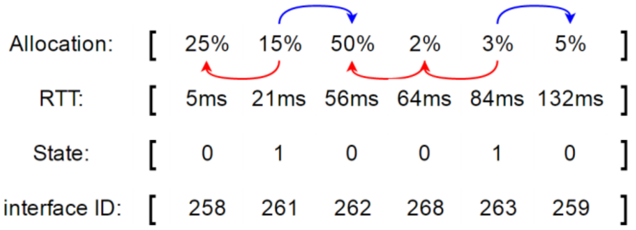

Figure 4 Operating Logic in HLAF

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[3] RTT in HLAF is defined as the RTT averaged within a short time window.

[4] We avoid using hop-count as it can be inaccurate in the overlay networks.

state = 0, an interface is able to claim traffic from other interfaces with larger RTT. In state = 1, an interface must distribute the congested traffic to another congestion-free interface with larger RTT. To deal with the adjustment between interfaces, HLAF keeps an array of allocation (in percentage) of eligible interfaces and forwarding interest based on the allocation. Note that the array is always sorted by the average of history RTTs.

As shown in Figure 4, in case of state = 1 (blue lines), the interface (e.g. ID = 261; ID = 263) is congested and will shift allocation to the right first congestion-free interface (e.g. ID = 262; ID = 259). In case of state = 0 (red lines), the interface (e.g. ID = 258; ID = 262; ID = 268) proactively claims the allocation from the right first interface (e.g. ID = 261; ID = 268; ID = 263).

Initially, the interface with shortest RTT (ID = 258) is initialized to 100% while 0% for all other paths. For each received NACK, the router reduces the forwarding allocation of the interface where NACK is back and increases the forwarding allocation of the right first congestion-free interface (with the smallest RTT) as below:

$$\Delta L = P(F_C) \times \eta$$
$$P(F_C) := P(F_C) - \Delta L$$
$$P(F_I) := P(F_I) + \Delta L$$

Where ΔL denotes the allocation shifted from the congested interface to the congestion-free interface. $P(F_C)$ denotes the forwarding allocation of congested interface F_C, $P(F_I)$ denotes the forwarding allocation of the right first congestion-free interface F_I.

For the congestion-free interface, the router claims the forwarding allocation of the interface from the right first interface (no matter congestion or not) as below:

$$\Delta K = P(F_B) \times \lambda$$
$$P(F_B) := P(F_B) + \Delta K$$
$$P(F_D) := P(F_D) - \Delta K$$

Where ΔK denotes the allocation shifted from the larger-RTT interface to the smaller-RTT interface. $P(F_B)$ denotes the forwarding allocation of congestion-free interface F_B, $P(F_D)$ denotes the forwarding allocation of the right first interface F_D. The congestion-free is detected by not receiving any NACK for at least 100ms. After adjustment, if the congestion-free interface is congested again, the extra allocation will be shifted to the rest congestion-free interface as NACK is received. Notice that, congestion potentially increases RTT of the received packets. Thus the routers are required to re-sort the array until RTTs are in the right order.

D. *Failure Detection*

For the disconnected link, all forwarded interests will be lost. HLAF enables the router to recognize the failure if an interface has timeout ratio as 100% (i.e. no data packet are returned). In this case, the interface is marked as failure and is not allowed for forwarding until recovery.

E. *Recovery Probing*

In some case, the link failure is temporary. The strategy is also responsible for probing the failed interface. HLAF employs NULL (encapsulated in an interest packet) packets to detect the connectivity. After an interface is failed, the router periodic forwards NULL packets to this interface, if the link is recovered, the content producer that receives a NULL packet will return an ACK (encapsulated in a data packet) packets to confirm the connectivity. Different from using duplicated interest/data packets to probe the connectivity, the size of NULL and ACK packets is trivial, which will not lead to large overhead.

IV. PERFORMANCE EVALUATION

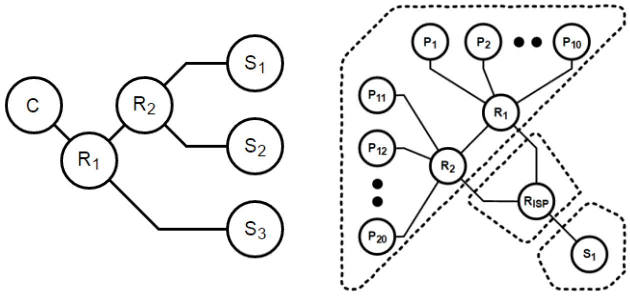
We studied the performance of the proposed solution by a ns3-based simulator ndnSIM [15]. The evaluation contains two experiments. First, we show the effectiveness of HLAF on the multisource (multipath) communication with different latency configurations. Second, the peer-assisted video streaming with different strategies is compared with the server-only approach. The video streaming simulation evaluates the performance via 4 metrics: 1) downloading speed, 2) round-trip time, 3) QoE – playback stalling time [16] and 4) QoE – playback quality [16].

The clients/peers employ a TCP-like congestion control (AIMD) to adapt a client’s data requesting rate. This is confirmed by the developments of Future Internet community [17]. The implementation follows the CHoPCoP design [18], which increases the congestion window if all packets are received and cut down the rate according to the percentage of received congestion notifications (i.e. NACK packets in this paper). The capped requesting rate a client is 200 packets (MTU = 1500Byte) per second, which is equal to 2.4Mbps downloading speed.

For video streaming, testing videos are split every 2 seconds and encoded into 5 representations (~830, 1172, 1363, 1712, 2344 kbps) via the Scalable Video Coding (H264-SVC) standard which enables reusing the lower layers for higher quality playback [19]. Due to the multipath characteristic, peers adapt the video quality via the buffer-based adaptation logic [7].

Four different forwarding strategies compared with the proposed HLAF include:

- ***SRTT*** [20] : The router estimates RTT based on the smoothed-RTT solution [20] and selects the interface with the least SRTT for forwarding.



(a) Multi-source Communication (b) Peer-assisted Video Steaming
Figure 5 Topologies

- ***RFA*** [14] : The router counts the amount of unsatisfied pending interests (PI) of each interface and distributes the interests to equalize the PI of different interfaces.
- ***PAF*** [9] : It is forwarding strategy inspired by Ant Colony Optimization (ACO). The router calculates Pheromone table via the RTT metric.
- ***PCON*** [21] : A recent forwarding strategy that adjusts the forwarding probability based on explicit congestion notification.

A. Multipath Communication

We use the topology in Figure 5 (a) to assess the performance of the proposed HLAF strategy to the conventional strategies. We considered a 6-node topology to be sufficient validating the idea and examining the performance. The consumer (C) can access the content from different producers (S_1, S_2 and S_3). The latencies and capacities of links are **artificially designed** to be different but practical, which highlights the challenge of the multi-source communications in real-world (e.g. CDN and P2P).

Two sets of link configurations are studied for different scenarios: 1) under-load and 2) critical-load. The first experiment stresses the characteristics of different strategies in case of the network can handle the traffic without congestion. The second experiment tests if a strategy can work properly if the network capability just satisfies the requirement of consumers. Notice that, the critical-load performance also reflects the over-load performance. If a strategy cannot properly utilize the resources in the critical-load scenario, it is not prospected to work well in the over-load scenario.

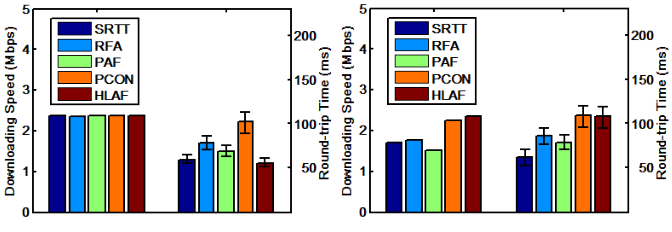
Under-load Scenario

The links are configured as C–R_1 (20Mbps/5ms), R_1–R_2 (10Mbps/10ms), R_2–S_1 (3Mbps/10ms), R_2–S_2 (3Mbps/20ms) and R_1–S_3 (800Kbps/50ms). As the consumers' requesting rate is capped at 2.4Mbps, either the path C–R_1–R_2–S_1 or the path C–R_1–R_2–S_2 can satisfy the requirement.

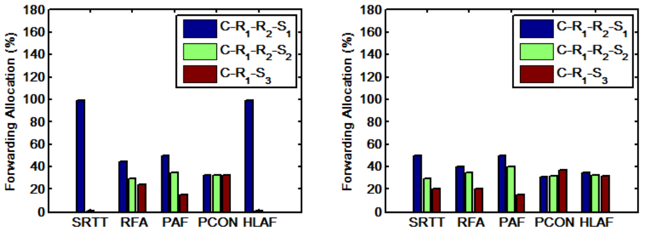
The result in left part Figure 6 (a) indicates that all conventional strategies can satisfy the requirement as the network is not congested. The right part of Figure 6 (a) illustrates the RTT of each strategy. Significantly, the mean RTTs and variance RTTs of SRTT and HLAF strategies are lower than other strategies. The allocation percentages that are shown in Figure 6 (c) provide some clues. SRTT or HLAF solely distributes the traffic to the single path (C–R_1–R_2–S_1) with the smallest latency. As RFA always softly select the interface with minimum pending interest for forwarding, it inevitably concurrently utilizes all paths. In RFA, the path with smaller latency is allocated with more traffic [11]. PAF performs similar as RFA but is more aggressive to latencies. PCON evenly distributes the traffic on each path, as the path (C–R_1–S_3) with the shortest distance has less bandwidth (800Kbps). Following the principle of PCON, the path with shortest distance will always assigned with more bandwidth if not congested. As C–R_1–S_3 does not have sufficient bandwidth, PCON distributes the traffic to the rest paths evenly, which causes the equal allocation among three paths. As RFA, PAF and PCON distribute traffic to all paths simultaneously, the paths with longer latency increase the mean RTT and also raise the variance.

Critical-load Scenario

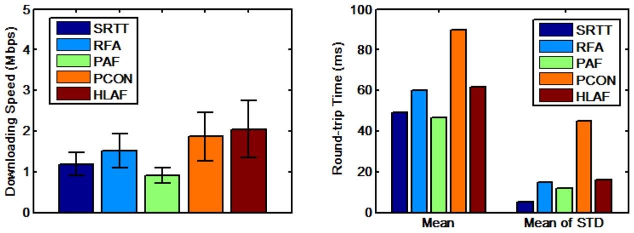
The links are configured as: C–R_1 (20Mbps/5ms), R_1–R_2 (10Mbps/10ms), R_2–S_1 (800Kbps/10ms), R_2–S_2 (800K bps/20ms) and R_1–S_3 (800Kbps/50ms). As the consumers' requesting rate is capped at 2.4Mbps, all three paths C–R_1–R_2–S_1, C–R_1–R_2–S_2



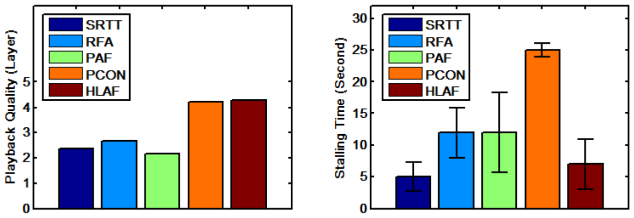
(a) Speed & RTT in under-load (b) Speed & RTT in critical-load



(c) Allocation in under-load (d) Allocation in critical -load
Figure 6 Scenario: Under-load



(a) Downloading Speed (b) Round-trip Time



(c) QoE – Playback Quality (d) QoE – Stalling Time

Figure 7 Scenario: Under-load

and C–R_1–S_3 are required to be fully utilized to satisfy the requirement (2.4Mbps).

As shown in the left part of Figure 6 (b), only the HLAF and PCON strategies nearly satisfy the requirement which the rest can only achieve at most 70%. Figure 6 (d) gives the reason of that, either the RTT-based (SRTT or PAF) or PI-based (RFA) strategy biases against the path with smaller latency, which overloads paths unnecessarily and reduce the total throughput [11]. Even though HLAF uses RTT to evaluate the interfaces auxiliary, the congestion-level detected by NACK avoids overusing the congested paths. The utilization of PCON is similar but slightly lower than HLAF. We consider the reason as PCON moves the allocation from the congested interface to other interfaces blindly, which may exacerbate the congestion of some interfaces. As both HLAF and PCON concurrently utilize all paths, the RTT shown in the right part of Figure 6 (b) is inevitably higher than the rest.

The two experiment shows that HLAF can effectively select the least amount of paths with smaller RTT and satisfy the requirement, which can well fit the video-streaming applications.

B. *Peer-Assisted Video Streaming*

The peer-assisted video considers a more practical topology in Figure 5 (b). This experiment mainly concerns about the performance between the peer-assisted video streaming and the server-only video streaming.

The whole network contains three areas. The green area denotes the user network, where P2P and HLAF are solely deployed inside this area. The brown area simulates the core network, where the default forwarding strategy[5] is deployed here. The blue area denotes the server network, where the provided videos are placed here. Inside the user network, 20 peers are deployed in the user network. The links between clients and gateways are configured as random bandwidths from 2Mbps to 20Mbps with the mean of 5Mbps. The latencies between clients (peers) and gateways are set from 2ms to 30ms with mean of 10ms. The connection between gateways is set to 50Mbps/10ms. The connection between the gateways and the inter-network router is set to 15Mbps/30ms. The connection between inter-network router and the server node is 25Mbps/30ms. The video streaming applications of peers start randomly (~ uniform distribution) from 0s to 300s. After every 20 chunks are downloaded, the peer publishes them to the network.

Figure 7 (a) demonstrates the downloading speed of the server-only video streaming and the peer-assisted video streaming with different strategies. Unsurprisingly, by deploying HLAF and PCON, the peers' downloading speed is increased. However, the other strategies can also enhance the forwarding rate but less significant. The rationale behind has been discussed in the Section IV.A. As the latency between peer-peer and peer-server can be different, the RTT-based and PI-based strategies will overload some peers (with smaller latency) but always under-load the server. Figure 7 (b) illustrates the mean and the mean of the standard derivation (STD) of RTT (i.e. estimating the STD of RTT for each peer) in different approaches. We could find out that the mean of STD of RTT in HLAF is much smaller than PCON. This is because HLAF prefers to fill the paths with smaller latency one-by-one. Figure 8 (c) and (d) presents QoE of different approaches. As the latency of HLAF is smaller and stable than PCON, it enables the similar quality playback and much lower stalling time.

V. RELATED WORK

Existing works on P2P are mainly focusing on verifying the feasibility of P2P over NDN and the application protocol design. A mediator approach proposes Detti *et al.* [22] first discovers the addresses of peers and then uses these addresses to fetch the content from a specified peer. To the best of authors' knowledge, limited studies were proposed to investigate the clean-slate P2P architecture. The solution proposed by You *et al.* [23] separately designed of the P2P forwarding table from the original one. However, the paper has not considered the limitation of peers' uploading ability.

In adaptive forwarding area, extensive studies have been proposed to support the multi-source communications. INFORM [24] is an adaptive hop-by-hop forwarding strategy using reinforcement learning inspired by Q-routing, which discovers temporary copies of content not presented in the routing table. Probability-based Adaptive Forwarding is novel solution inspired by ant colony optimization, which selects the interfaces based on an RTT distribution. On-demand Multi-Path Interest Forwarding [10] allocates traffic to disjoint paths via the weighted round-robin scheme based on the round-trip time of each path. Via emulating the liquid piping system, Stochastic Adaptive Forwarding proposed Daniel *et al.* [25] provides a robust traffic allocation even

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[5] In practice, the forwarding and routing are usually customized by ISP

with incomplete routing information. Carofiglio *et al.* [14] proposed an optimal forwarding strategy via solving the multi-flow minimum-cost problem approximately, which uses the number of pending interests as the factor to evaluate the forwarding interfaces

VI. CONCLUSION

This paper presented a practical clean-slate P2P design – Peer-Assisted Video Stream in NDN and proposed an adaptive forwarding strategy – HLAF to effectively support peer-assisted video stream. The proposed bit-field method enables peers to publish content in an efficient manner and HLAF allows peers to download content from each other without overloading any individual peer. The experiment shows that HLAF can effectively utilize multiple paths with smaller RTT. Meanwhile, HLAF is shown to outperform other conventional strategies in largely reducing the stalling time and increase the playback video quality.

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