Exponential Interest Aggregation for Hop-by-hop Congestion Control in NDN

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***Abstract*—Named Data Networking (NDN) is one of the most promising Information-Centric Networking (ICN) oriented projects aiming to satisfy the new requirement of content communication. Congestion control is the key issue when designing NDN transport protocol. Hop-by-hop congestion control schemes have been developed recently. However, existing hop-by-hop schemes lack adaptivity to network status. In this paper, we propose Exponential Interest Aggregation (EIA), an adaptive forwarding strategy addressing NDN congestion control problem in a hop-by-hop manner. We establish the Interest aggregation state transition model and analyze the effectiveness of EIA algorithm mathematically. Extensive simulation is carried out to evaluate the performance of EIA algorithm and comparisons are drawn with existing forwarding strategies. The results show that EIA outperforms existing schemes in terms of delay, number of retransmission and cache hit ratio. In particular, EIA improves average delay by 13%, average number of retransmission by 25% and cache hit ratio by 61%.**

***Index Terms* – NDN, Congestion Control, Interest Aggregation, Forwarding Strategy**

I. INTRODUCTION

For more than five decades, IP architecture has worked relatively well as a solution to the networking problem of resource sharing. IP Protocol was proposed when the basic requirement of Internet was merely forwarding packets between end hosts. Therefore IP adopted a host-centric communication model which aimed at providing point-to-point conversation between hosts.

The rapid advancement of technology in network equipment and end devices, along with the tremendous growth of the Internet gradually shapes the network demands towards new requirements such as support for scalable content distribution, mobility, security, trust, etc [1]. However, current IP architecture cannot deal with these issues quite well. Since data communication today is about moving content, the concept of content-centric networking (or information-centric networking, in a broader sense) has received much attention in recent years to satisfy these requirements.

Content-Centric Networking (CCN) was first proposed by Jacobson in 2006 and was formally formulated in 2009 [2]. CCN is a networking architecture built on IP's engineering principles, but using named content rather than host identifiers as its central abstraction. In addition, CCN puts emphasis on security and strategy. Apart from CCN, there are numerous other ICN-related projects, such as DONA [6] project at Berkeley, PURSUIT [7], SAIL [8], COMET [9], CONVERGENCE [10], all established by Europe, and MobilityFirst [11] by US, etc.

Named Data Networking (NDN), proposed by Zhang et al. [3], is one instance of information-centric networking which follows the direction of CCN. Communication in NDN is receiver-driven. To request the desired data, the consumer sends an Interest packet into the network. If any node in the network contains the data specified in the Interest packet, it forwards the Data packet back to the network through the reversed path taken by the Interest packet. This remarkable shift results in a new network forwarding plane.

Forwarding plays a pivotal role in NDN architecture and is closely related to congestion control. For every NDN node, a forwarding strategy determines whether and when to forward a packet as well as which interface(s) the packet should be forwarded to. Besides, the forwarding strategy controls the frequency of Interest retransmission given that the previous Interest requests are failed. All of these issues can considerably affect the network congestion level. Hence the forwarding strategy should be carefully designed to cope with dynamic network status.

Initially, four forwarding strategies were proposed and implemented in NDN Forwarding Daemon (NFD) [12], a network forwarder that implements the Named Data Networking protocol. The four strategies are: best route strategy, broadcast strategy, client control strategy and NCC strategy.

The best route strategy forwards an Interest to the upstream interface with the lowest routing cost. After that, if a similar Interest arrives from another downstream interface, the Interest is aggregated if it's within Minimum Retransmission Interval (MRI), otherwise it is retransmitted. A retransmitted Interest is forwarded to the lowest-cost nexthop that is not previously used, except downstream; if all nexthops have been used, it is forwarded to the nexthop that was used earliest.

At the other end of the spectrum from best route strategy lies broadcast strategy. The broadcast strategy simply forwards every Interest to all upstream interfaces, indicated by the FIB

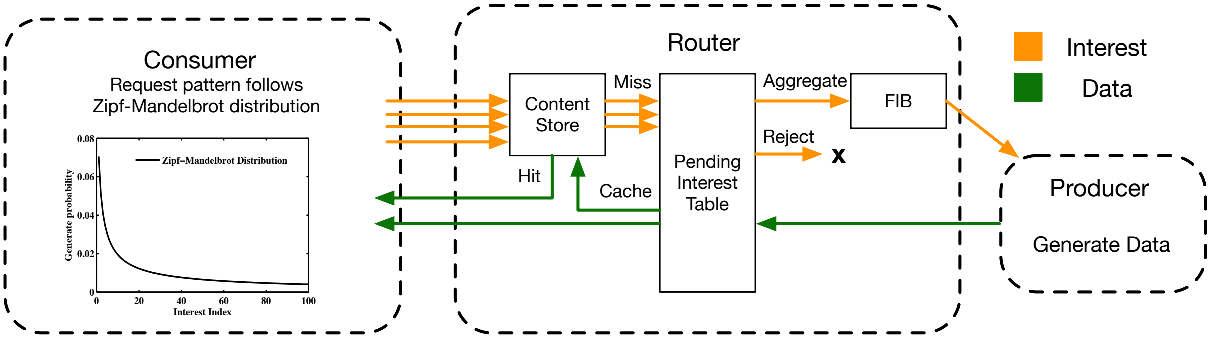

Fig. 1. Network Overview

entry. The client control strategy allows a local consumer to choose the outgoing interface of each Interest. The NCC strategy is an reimplementation of CCNx 0.7.2 default forwarding strategy [31].

Tortelli et al. [13] compared the performance of best route strategy and broadcast strategy. They showed that in terms of mean download time and hit distance, the broadcast strategy performs better, whereas the best route strategy incurs much less overhead and reduces the load in the network. In reality where the number of nodes is large, the broadcast strategy is not likely to scale well and tend to cause congestion. A feasible forwarding strategy should be adaptive to the network status such as congestion and link failures, etc [5].

Congestion control in NDN/CCN can be achieved by Interest aggregation. Since over each link, one Interest packet can only bring back no more than one Data packet, NDN guarantees one-on-one flow balance. Therefore, to prevent congestion, it is sufficient to control the Interest flow in advance. Interest aggregation provides the ability to reduce the network load when multiple interests requesting the same content are received from different sources [14]. This is accomplished by aggregating and merging them in the router, forwarding a single interest upstream and carrying downstream a single copy of the corresponding content.

Interest aggregation in NDN's best route strategy is achieved by setting the Minimum Retransmission Interval (MRI). However, the current best route strategy is not adaptive to network status. The MRI is set to a fixed value. We propose a new forwarding strategy in which the retransmission interval varies according to the congestion level in the network. Specifically, we use Exponential Interest Aggregation (EIA) algorithm to adjust the MRI in order to get rid of congestion quickly and efficiently.

In this paper, we focus on hop-by-hop congestion control in Named data networking. In particular, we study the model of Exponential Interest Aggregation. Though our work is mainly in the context of NDN, it can also provide some insights into the congestion control in information-centric networks in general.

We present network description and assumptions in Section II. In Section III, we propose Exponential Interest Aggregation (EIA) strategy. We evaluate and analyze the performance of EIA in section IV. Finally, we summarize the related works in Section V, and conclude this paper with some discussion in Section VI.

II. Network Description

We consider a network with three sets of nodes: consumer, router and producer. A set of N contents exists in the network. The network overview is depicted in Figure 1.

Consumers generate Interest packets at constant rate, requesting different Data. The consumer's Interest generation pattern follows Zipf-Mandelbrot distribution [27]. Zipf-Mandelbrot distribution is typically used to capture the popularity of different contents. The probability mass function is given by:

$$f(k; N, q, s) = \frac{1/(k+q)^s}{H_{N,q,s}}$$

where $H_{N,q,s}$ is given by:

$$H_{N,q,s} = \sum_{i=1}^{N} \frac{1}{(i+q)^s}$$

Routers forward Interest packets to upstream producers and bring Data packets back to downstream consumers. Each router maintains three data structures: a Pending Interest Table (PIT), a Forwarding Information Base (FIB), and a Content Store (CS) with limited size [4]. Content Store is utilized to achieve in-network caching. Routers do not generate Interest packets during the whole forwarding process.

When an Interest packet arrives at a router, the router first checks its Content Store. If there is a match, which means it has cached the corresponding Data, the router sends back the Data packet to the incoming face. If there is a miss in Content Store, the router determines whether and how to forward the Interest according to the forwarding strategy it adopts.

When a Data packet arrives at a router, the router first check the Data's name in its PIT. If there is no matching PIT entry, the Data is simply discarded. If there exists a matching in PIT, the router forwards the Data packet to all the faces with a pending Interest for the Data. Before removing the PIT entry, the router determines whether to cache the Data packet in its Content Store.

Producers possess all the contents requested by the consumers in the network. Upon receiving an Interest, the producer immediately forwards the Data packet to the incoming interface.

We consider a network in congestion. Since we assume a constant Interest generation rate of consumer and fixed link bandwidths, the network throughput is relatively steady. Due to the network congestion, the packet loss rate is high, causing numerous Interest retransmissions. In addition, under this steady network setting, the packet loss rate stays constant.

III. Exponential Interest Aggregation

Based on RTT estimation, existing forwarding strategies mainly determine the interface(s) i.e. the nexthop of the forwarding Interest. However, our forwarding strategy focuses on determining whether an Interest should be forwarded to a nexthop.

First consider an ideal condition where no packets are lost during transmission in the network. When a router forwards an Interest, it is guaranteed to receive the corresponding Data. Hence if the router then receives an Interest requesting the same Data, it simply waits for the Data instead of forwarding the Interest again. In a congested network however, forwarding an Interest may not bring back the corresponding Data due to packet loss, and thus Interest retransmission is required. This gives rise to the problem of whether and how frequently for a router to retransmit an Interest.

One simple approach to deal with Interest retransmission is to forward the Interest immediately after receiving. This approach is used by the broadcast strategy. As a consequence, if the consumer retransmits Interests too frequently, the network is likely to be flooded by duplicate Interest and Data packets. The second kind of strategy seeks the solution in the router itself. It sets a threshold for Minimum Retransmission Interval (MRI). When an Interest packet is received at a router for the first time, it is forwarded immediately and a timer is set to the threshold. If the incoming Interest requesting the same Data arrives before the timer expires, the router aggregates this Interest by only adding the incoming face to PIT entry with no retransmission. Otherwise, the router retransmits the Interest, assuming that the last Interest request failed. This is a hop-by-hop congestion control mechanism because each router can decide whether the Interest should be forwarded or not.

Our Exponential Interest Aggregation (EIA) strategy focuses on the adaptive optimization of the second solution. The originally fixed threshold, that is, the Minimum Retransmission Interval, is exponentially increased to better control network congestion. In the following sections, we first propose our EIA forwarding strategy in detail. Then we formulate the aggregation model as a state transition diagram. Finally, we analyze the performance of EIA mathematically.

A. EIA Strategy Design

In this section, we present the Exponential Interest Aggregation strategy. EIA realizes per-Interest congestion control at every router. Each NDN router adopts EIA to achieve congestion control in a hop-by-hop manner.

EIA is designed to address the concern of adaptivity to network status. When sensing congestion, EIA exponentially increases Minimum Retransmission Interval. When the network congestion is mitigated, EIA resets the MRI back to the initial value. In this manner, EIA achieves adaptivity.

The router's capacity for Interest aggregation is closely associated with its ability to control network congestion. This capacity is proportional to the length of MRI. As its name implies, EIA exponentially increases this capacity in order to get rid of congestion in a short period. Once the congestion is over, the aggregation capacity is reduced to initial setting to fully utilize the bandwidth resource.

MRI should not increase to infinity since it is meaningless for MRI to be larger than PIT entry existence time. Therefore a maximum number of exponential increase is enforced on MRI.

The EIA forwarding strategy works as follows. Upon receiving a subsequent Interest, the router chooses to aggregate it if its arrival time is within the MRI. Otherwise the router retransmits the Interest and increases the MRI by an exponential factor. The router then chooses the interface to which the Interest is forwarded. In EIA, the interface with the lowest cost is chosen to forward the Interest. When receiving a Data, the router resets the MRI of the corresponding Interest to initial value and forwards the Data to all the pending interfaces.

The aggregate algorithm is illustrated by the Algorithm 1 and the overall EIA forwarding strategy is presented in Algorithm 2.

Algorithm 1 Exponential Interest Aggregation

function AGGREGATE($Interest, PIT$)
  if $IntEntry \leftarrow PIT.Find(Interest.Name)$ **then**
    if $Interest.ArrTime - InitTime \leq MRI$ **then**
      $IntEntry.InFace.Add(Interest.face)$
    else
      if $Interest.RC \leq M$ **then**
        $Interest.MRI \leftarrow Interest.MRI \cdot r$
      end if
      FORWARD_INTEREST($Interest, FIB$)
      $InitTime \leftarrow Interest.ArrTime$
      $Interest.RC \leftarrow Interest.RC + 1$
      $IntEntry.InFace.Add(Interest.face)$
    end if
  else
    $Interest.RetransCount \leftarrow 0$
    $Interest.MRI \leftarrow W_0$
    $PIT.Add(Interest)$
    FORWARD_INTEREST($Interest, FIB$)
  end if
end function

Algorithm 2 EIA Forwarding Strategy

```
function FORWARD_INTEREST(Interest, FIB)
    FIB.face.Sort(cost)
    if Entry ← FIB.Find(Interest.Name) then
        for each face ∈ Entry by rank do
            if face ∉ Interest.face then
                if face.Available then
                    Transmit(Interest, face)
                end if
            end if
        end for
        Discard(Interest)
    else
        Discard(Interest)
    end if
end function

function FORWARD_DATA(Data, PIT)
    if IntEntry ← PIT.Find(Data.Name) then
        for each face ∈ IntEntry.InFace do
            Transmit(Data, face)
        end for
        IntEntry.MRI ← W_0
    else
        Discard(Data)
    end if
end function
```

B. Model Formulation

The transition probability p_c between any two sequential states is the same. To illustrate this property, we first denote the probability of Interest or Data packet loss as p_l and the probability of receiving the data packet which is already timeout as p_t. Then p_c can be expressed as the sum of p_t and p_l. As stated in previous section, the packet loss rate is high in the congested network setting. As the interval W_i increases exponentially, p_t reduces to zero, so the probability of packet loss is much greater than p_t. Therefore p_c equals to loss rate p_l, which is a constant value. Thus, p_c can be viewed as a constant between any two sequential states.

Detailed interpretation of the model is as follows. W_i is the length of MRI in state i. Specifically, W_0 is the initial MRI, W_i = $r \cdot W_{i-1}$ for any i and $W_i = r^i \cdot W_0$. p_i denotes the probability that an interest receives its data packet after retransmitted i times, indicating that the first $i-1$ (re)transmissions all failed. I_t is the t^{th} state of a pending interest. I_t can only be S_0 or S_t because S_i can only transit to S_{i+1} or S_0.

In the following subsections, we analyze the performance of EIA strategy mathematically. For the purpose of analysis, we consider state transition diagram presented in Figure 2. The model is characterized by a single router controlling over a sequence of subsequent Interests. The notations are depicted in Table 1.

The transition probability between different states are given

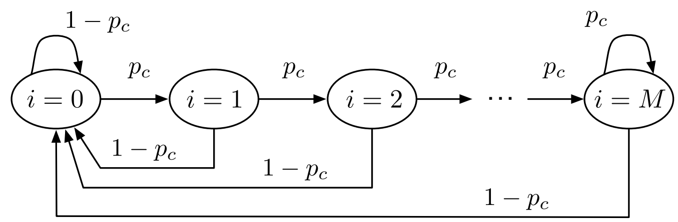

Fig. 2. State transition diagram

Variable	Explanation
r	Exponential factor
W_i	MRI in state i
S_i	i^{th} state which has MRI of W_i
p_c	Transition probability from state i to state $i+1$
p_i	Probability that the i^{th} retransmission brings the data
I_t	The t^{th} state of a pending interest
D_i	Total delay after retransmitted i times
M	Maximum number of times the MRI can exponentially increase

TABLE I
NOTATIONS

as follows [26]:

$$p_{i,0} = p(I_{t+1} = S_0 | I_t = S_i) = 1 - p_c$$

$$p_{i,i+1} = p(I_{t+1} = S_{i+1} | I_t = S_i) = p_c$$

$$p_{i,j} = p(I_{t+1} = S_j | I_t = S_i) = 0 \quad \forall j \neq i+1 \text{ or } 0$$

The probability that an interest successfully receives its data packets after retransmitted i times is

$$p_i = p_c^i \cdot (1 - p_c)$$

It is because $p_i = p_{i-1} \cdot p_c$ and $\sum_i p_i = 1$.

C. EIA Analysis with Infinite Increase

We first analyse EIA in a simple setting where the MRI could increase to infinity.

1) Number of Transmission: The expectation of the number of transmission is given by

$$E[i+1] = \sum_i (1 - p_c) \cdot p_c^i \cdot (i+1) = \frac{1}{1 - p_c}$$

2) Delay: The delay in state i is

$$D_i = W_0 + W_1 + ... + W_i = W_0 \cdot \frac{r^{i+1} - 1}{r - 1}, \ \forall i = 0, ..., M$$

Thus, the expectation of total delay is calculated by

$$E[D_i] = \sum_i W_0 \cdot \frac{r^{i+1} - 1}{r - 1} \cdot p_c^i \cdot (1 - p_c)$$

The expectation consists of sums of two geometric sequences with common ratios p_c and $r \cdot p_c$. The ratio of the first sequence p_c is less than 1 by definition, whereas the the ratio of the second sequence $r \cdot p_c$ is not guaranteed to be less than 1. If $r \cdot p_c$ is greater than or equal to one, the delay will approach infinity and the network cannot stay steady. Thus, $r \cdot p_c$ must be less than one under our assumption and the expectation is

$$E[D_i] = \frac{W_0}{1 - r \cdot p_c}$$

D. EIA Analysis with Finite Increase

In real network settings, the MRI cannot increase to infinity. Its value is upper-bounded by the PIT entry existence time. Therefore the number of times that MRI could exponentially increase is upper-bounded, and in EIA strategy, by a positive integer M. In this subsection, we present the analysis of EIA with finite increase.

1) Number of Transmission: Given r, W_0, the expectation of transmission times is given by

$$\begin{aligned} E[i+1] &= \sum_{i=0}^{M} (1-p_c) \cdot p_c^i \cdot (i+1) \\ &+ \sum_{i=M+1} (1-p_c) \cdot p_c^i \cdot (M+1) \\ &= \frac{1-p_c^{M+1}}{1-p_c} + (M+1) \cdot p_c^{M+2} \end{aligned}$$

2) Delay: Given r and W_0, the delay in state i is

$$D_i = \begin{cases} W_0 \cdot \frac{r^{i+1}-1}{r-1}, & i \leqslant M, \\ W_0 \cdot \frac{r^{M+1}-1}{r-1} + W_0 \cdot r^M \cdot (i-M), & i > M, \end{cases}$$

Thus, the expectation of delay is

$$\begin{aligned} E[D_i] &= \sum_{i=0}^{M} W_0 \cdot \frac{r^{i+1}-1}{r-1} \cdot (1-p_c) \cdot p_c^i \\ &+ \sum_{i=M+1}^{\infty} \left(W_0 \frac{r^{M+1}-1}{r-1} + W_0 r^M (i-M) \right) (1-p_c) p_c^i \\ &= \frac{W_0 \cdot (1-p_c) \cdot r}{r-1} \cdot \frac{1-(r \cdot p_c)^{M+1}}{1-r \cdot p_c} \\ &+ W_0 \cdot (r \cdot p_c)^M \cdot \frac{p_c}{1-p_c} - \frac{W_0 \cdot \left(1-(r \cdot p_c)^{M+1}\right)}{r-1} \\ &= \frac{W_0 \cdot \left(1-(r \cdot p_c)^{M+1}\right)}{1-r \cdot p_c} + W_0 \cdot (r \cdot p_c)^M \cdot \frac{p_c}{1-p_c} \end{aligned}$$

The calculation of the expectation of delay uses

$$\sum_{i=M+1}^{\infty} i \cdot p_c^i = \frac{(M+1) \cdot p_c^{M+1}}{1-p_c} + \frac{p_c^{M+2}}{(1-p_c)^2}$$

IV. Evaluation

We implement EIA strategy and evaluate its performance in *ndnSIM* [28][29], a simulator based on ns-3 [32]. Extensive simulation is carried out in various network scenarios, and results show that EIA strategy outperforms existing strategies in terms of throughput, delay, number of retransmission, and cache hit ratio.

A. Experiment Settings

We compare our proposed EIA strategy with three existing forwarding strategies – broadcast strategy, NCC strategy, and fixed strategy. We refer to original "best route strategy" as "fixed strategy", as distinct from EIA strategy.

The simulation topology is presented in Figure 3. There is one consumer (node 0) and one producer (node 8). All the other nodes function as router. We choose this topology for this regularity and symmetry.

The request rate of the consumer is $10,000$ packets per second. All Data packets have equal size of 1 KB. Each link has bandwidth of 1 Mbps. In-network caching enabled in every router has Content Store of size $1,000$ Data packets. There are in total $10,000$ different kinds of contents in the network. The content popularity, i.e. the request rate of a content, follows a Zipf-Mandelbrot distribution, and the distribution parameter is 0.7. Simulation lasts 300 seconds, and we record network status every 0.5 second. The MRI and exponential factor in our exponential algorithm are chosen as 100 and 2. Least recently used cache replacement policy is applied in every Content Store.

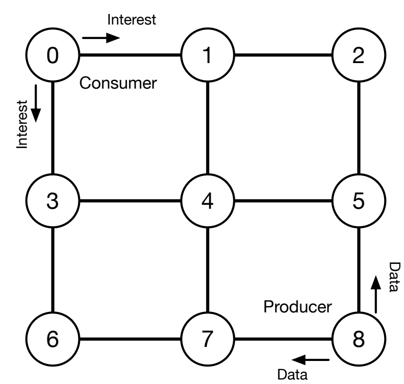

Fig. 3. Grid Topology

B. Metrics

Strategy performance is evaluated based on the following metrics.

- *OutInterest*: it measures the total size of Interest packets sent by the consumer in a unit time. Due to the characteristic of flow balance in NDN, OutInterest affects the network congestion level.
- *InData*: it calculates the total size of Data packets received by the consumer in a unit time. It measures user-level performance.
- *Average Delay*: it calculates the time interval between the first request of the consumer and the time the consumer finally receive the Data. It reflects user-level performance.
- *Number of Retransmission*: it implicitly reflects the loss rate, which affects the average delay. It is a metric useful to explain other metrics.
- *Cache Hit Ratio*: it is the ratio of the satisfied Interests at a node to the total Interests received by that node.

- *Loss Rate*: it is the number of lost Data packets in a unit time, influenced by both the cache hit ratio and the degree of duplicate Data packet.

C. Throughput Analysis

In Figure 4, we observe that EIA strategy incurs less Out-Interests than broadcast, fixed and NCC strategies. Moreover, it converges faster and has steadier performance from time to time. As for InData, EIA strategy, fixed strategy and NCC strategy can achieve approximately the same transmission rate after a short time. However, broadcast strategy suffers from considerable vibration and can only receive Data in a smaller average rate. This upper bound of the transmission rate results from the simulation setting. As the consumer has two connected links and the bandwidth of each link is 1Mbps, it can receive data in a rate of 2Mbps. Furthermore, since we sample every 0.5 second, the theoretical upper bound of transmission rate is 125 kilobytes per second, which matches perfectly in our simulation results.

Figure 4 also verifies the effectiveness of our network description, particularly the convergence assumption. Consequently, most of following analysis are made during period when network enters steady condition.

D. Delay and Number of Retransmission Analysis

We choose three different scenarios with three different time intervals, from 100 sec to 200 sec , from 30 sec to 150 sec, and from 0 to 300 sec. The first two time intervals are chosen when network is steady and the third one are chosen to cover the whole process.

As shown in Figure 5, EIA strategy performs much better than the other three strategies in terms of both average delay and average number of retransmission. Average delay measures user-level performance. The smaller average delay is, the better users will experience. Clearly, EIA strategy possesses the smallest average delay among all four strategies. Compared with the second-best strategy, EIA reduces the average delay by 13.57%, 12.48%, 6.94% in three scenarios, respectively. In addition, EIA also significantly reduces the average number of retransmission. Take scenario-1 for instance, it reduces approximately 6 times of Interest retransmission, compared with NCC strategy. Decreases in average delay and number of retransmission show the efficiency of EIA strategy.

E. Cache Performance Analysis

Different amount of network resources are consumed by Interest satisfied at routers with different distances. As a result, we analyze the hit ratio with different hop distances, and later focus on the hit ratio under one-hop distance, since it dominates the overall cache performance. As for the cache replacement policy, we adopt both Least Recently Used (LRU) policy and Least Frequent Used (LFU) policy.

As shown in Figure 6, EIA strategy obtains 60.9% relative performance improvement than the second best strategy with LRU policy. Among all combinations of strategies and cache replacement policies, EIA with LRU policy achieves the best hit ratio of 15.8864% and the EIA with LFU policy get the second place. This proves the stability of EIA strategy in terms of different replacement policies.

F. Loss Analysis

As shown in Figure 7, EIA strategy has the second-lowest loss rate at router, the lowest loss rate at producer, and the lowest average loss rate at all nodes. The loss rate caused by excessive Interest packets, as thus the small loss rate can manifest the low level of network congestion.

V. Related Work

Congestion control mechanism in TCP has been widely researched in the past, but in the context of information-centric networking, it has only recently been studied. In general, existing schemes fall into two categories: receiver-driven and hop-by-hop mechanisms [14].

Since ICN uses pull based transport model, it is intuitive to adopt the receiver-driven transport mechanism for ICN. At the beginning, most of the schemes and protocols were based on TCP's congestion control mechanism and adapt it to receiver driven context. ConTug [21] defines a split window which implements TCP protocol and raises a multi-window mechanism which allocates multiple windows according to the information source. ICTP [22] simply uses TCP congestion control schemes.

ICP (Interest Control Protocol), introduced in [16], was one of the earliest attempt to address the congestion problem with receiver-driven window-based AIMD algorithms. ICP uses Chunks packets and associated timers as signals to regulate the Interest sending rate at the receiver. However, the method ICP uses to set the timeout value is based on estimated RTT, which is not appropriate in CCN due to the variation and uncertainty of content store along the path. This mechanism was improved in [18], by adding route labels to Data so that multiple paths can be identified.

CCTCP [19] also represents a receiver-driven control solution. In CCTCP, the subsequent contents the receiver intends to request are listed in each interest packet. The receiver maintains separate congestion states for different content locations where future interest will be satisfied. As a result, CCTCP can reliably predict the location of content chunks before they are requested and consequently accurately estimate the retransmission timeout.

RRCP [20] is based on XCP and is a receiver-driven, multi-request windows and timeout mechanism. In order to accurately and quickly reflects the change of the network, a router-feedback mechanism is designed for the unpredictable cache sources. The feedback, containing all routers along the path, is put into the new defined congestion header instead of the router.

In receiver-driven window/rate-based schemes, estimation of RTT related to the content sources is heavily used. However, due to the caching nature of CCN, there often exists multiple sources of a content in the network, making the path length to a certain content varies. [23] shows that the receiver-driven

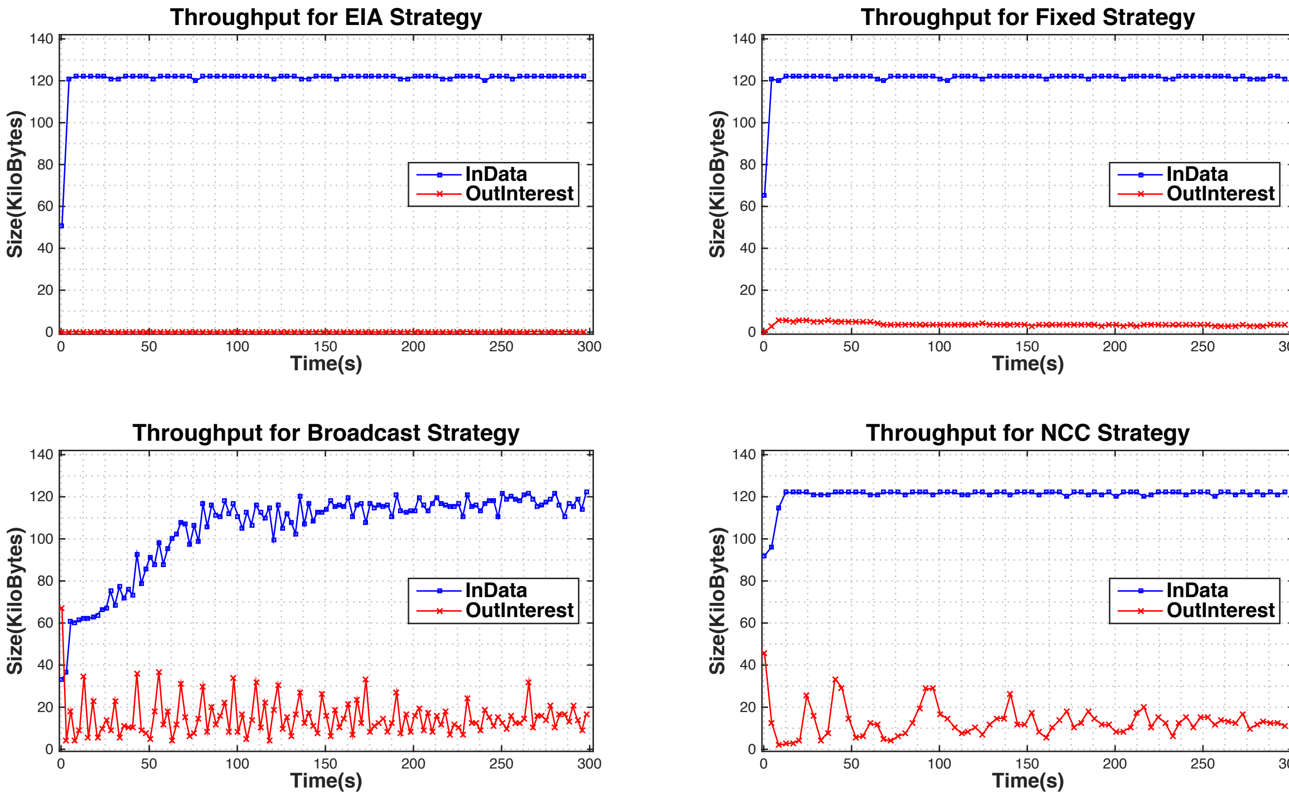

Fig. 4. Comparison of four strategies in congested network in terms of Throughput

solutions based on timeouts are not suitable for CCN because of the unpredictability of the content locations.

A second category of congestion control mechanism uses hop-by-hop interest shaping rather than letting the receiver infer network congestion using timeouts [14]. Rozhnova and Fdida [24] proposed HoBHIS, a hop-by-hop Interest shaping congestion control mechanism. HoBHIS monitors the transmission buffers of a CCN router to compute the Interests rate that have produced the associated Chunks filling these interfaces. This work was later improved in [14], which introduced an explicit Interest rate feedback mechanism designed to control the Client behavior and prevent a potential risk of network congestion.

Carofiglio et al. extend ICP [16] to a joint hop-by-hop and receiver-driven mechanism called HR-ICP [17]. It regulates user requests (Interests) either at the receiver or at intermediate nodes via Interest shaping. The mechanism proposed in [25] identifies the interdependence between the interests and its associated chunks and analyzes the fair resource allocation in presence of bidirectional traffic.

The work related to congestion control in CCN/NDN with hop-by-hop interest shaping mechanism has been developed recently. However, to the best of our knowledge, no existing work has taken Interest aggregation into account. The aim of this paper is to provide a new method to achieve congestion control in content-centric networking.

VI. Conclusion and Discussion

We present design, analysis and evaluation of Exponential Interest Aggregation (EIA), a forwarding strategy aiming to address congestion control in NDN. EIA solves the existing problems in best route strategy and enables routers to be adaptive to network status in a hop-by-hop manner.

We model the adaptive process as a state-transfer diagram and analyze EIA performance mathematically. We implement EIA forwarding strategy in ndnSIM. Through extensive simulation, we compare EIA with other three existing strategies. The re-sults show that EIA outperforms all other strategies in terms of average delay, number of retransmission, and cache hit ratio. In particular, EIA achieves 12.5% decrease in average delay, 25% decrease in average number of retransmission and 60.9% increase in cache hit ratio.

In this paper, we set the exponential factor of EIA strategy to be 2 and initial interval length of MRI to be 100 milliseconds. However, these two parameters can be altered based on the characteristic of different networks. For example, the exponential factor should be set to a smaller value accordingly, if the network is less sensitive to changes in throughput. Moreover, the initial MRI can be set to a larger value if we know beforehand that the current network is prone to suffer from severe congestion. Therefore, the effect of these two parameters in EIA strategy needs to be further studied.

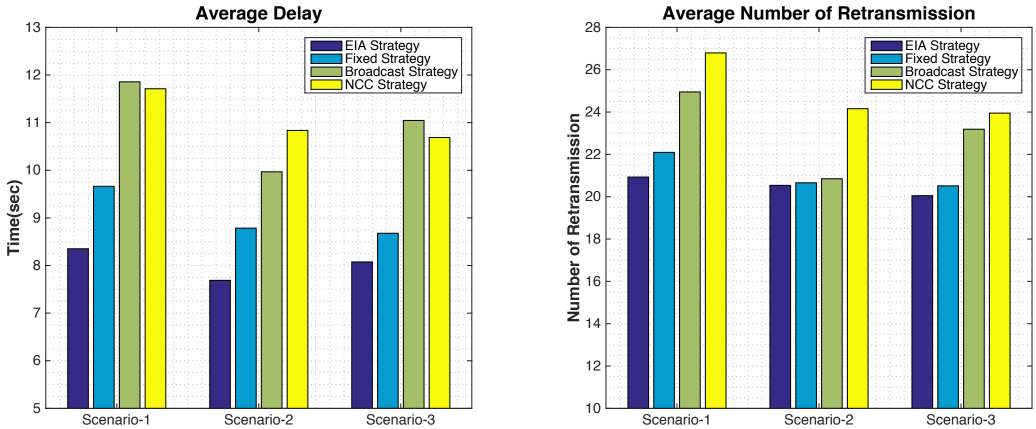

Fig. 5. Comparison of four strategies in three congested scenarios in terms of Average Delay and Average Number of Retransmission. Scenario-1 represents the time interval range from 100 sec to 200 sec. Scenario-2 represents the time interval range from 30 sec to 150 sec. Scenario-3 represents the time interval range from 0 sec to 300 sec.

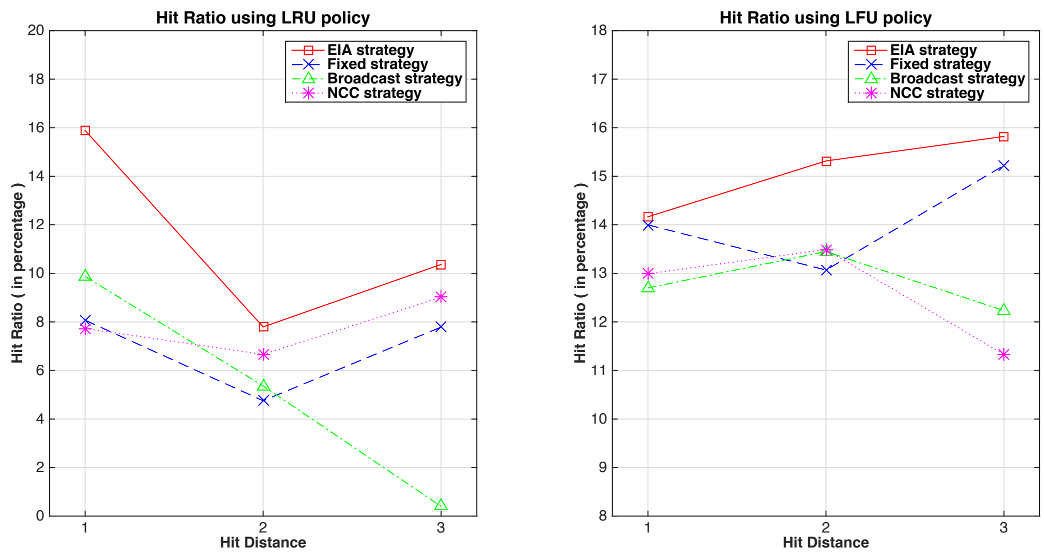

Fig. 6. Comparison of four strategies in terms of hit ratio under two different cache replacement policies.

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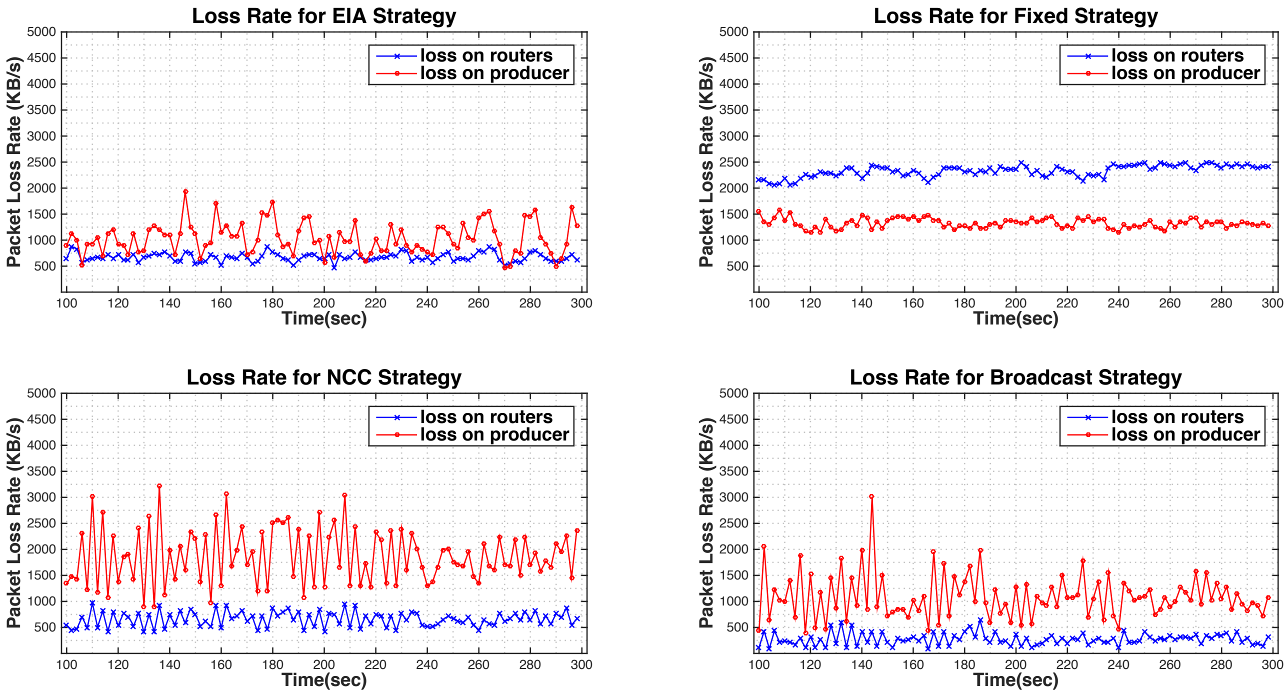

Fig. 7. Loss Analysis

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