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Modeling content transfer performance in information-centric networking

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HIGHLIGHTS

- We introduce the Markovian Queueing System theory into the ICN model.
- We develop an analytical model for content transfer performance in ICN. We derive expressions for the average content delivery time as functions of bandwidth/cache/buffer capacity, propagation delay, content popularity and other factors.
- Different from existing work, our model counts the complete delay including the queuing delay and the propagation delay in all links along the path, which makes it more accurate and practical.
- Our analytical results, supported by simulations, can be used as a reference for the design and evaluation of ICN architectures and protocols.

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ABSTRACT

Information-Centric Networking (ICN) is a promising future network architecture where content instead of its location becomes the core of the communication model. Content is independent from location, which enables in-network caching and sharing. Consequently, the transport mode changes dramatically. In this paper, we develop an analytical model for content transfer performance in ICN. We derive expressions for the average content delivery time as functions of bandwidth/cache/buffer capacity, propagation delay, content popularity and other factors, and then we specifically analyze the typical linear topology and the tree topology. Our analytical results, supported by simulations, can be used as a reference for the design and evaluation of ICN architectures and protocols.

1. Introduction

The traditional Internet architecture was originally designed for host-to-host text communication. Now, great changes have taken place in the scale and applications of the Internet. Humans have entered into the era of "Big Data" and the application mode has also been changed from text communication to information accessing and distribution. However, it is difficult for the current host-centric Internet architecture to accommodate these changes. Many problems emerge in terms of transport efficiency, security, mobility, etc. [1–3]. Some problems can be repaired by adding some patches. However, most of those patches increased the complexity of the overall architecture and proved to be only temporal solutions [4]. In addition, many current and emerging requirements still cannot be addressed adequately by the current Internet. Therefore, future Internet architecture has become a hot research topic.

In this context, Information-Centric Networking (ICN) [5] has emerged as a promising direction for the design of future Internet architecture. Many significant research projects have been funded in recent years focusing on the design of ICN architectures, such as data-oriented network architecture (DONA) [6], Publish–Subscribe Internet Routing Paradigm (PSIRP) [7]/Publish–Subscribe Internet Technology (PURSUIT) [8] and Content-Centric Networking (CCN) [9]/Named Data Networking (NDN) [10].

ICN tries to evolve the Internet architecture to directly support information distribution by introducing uniquely named data as the core of the architecture instead of its physical location. Content is independent of its location, which enables in-network caching and sharing. Therefore, content requests can also be served by caches along the path rather than only by the provider. As a novel architecture, ICN has obvious advantages over TCP/IP architecture,

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such as high transfer efficiency, mobility support and security. The in-network caching is an obvious new feature of ICN and changes the network transport mode dramatically. Analyzing and understanding the new transport mode will benefit the design of new architectures and optimized protocols.

In this paper, we focus on the performance evaluation of transport in ICN networks and develop an analytical model for content transfer under limited bandwidth and storage resources. Here, we focus on the content delivery time as a key performance metric to model content transfer performance in ICN, since the high transport efficiency is one of the big advantages of ICN compared with the traditional TCP/IP architecture, especially in the content distribution scenarios. We assume that content items are permanently stored in the repository (provider) and are partly cached with the least-recently used (LRU) per-packet replacement policy in the intermediate nodes according to the content popularity distribution. Each consumer is supposed to implement a receiver-driven transport protocol to retrieve content by sending requests. Under these assumptions, we derive expressions for the average content delivery time as functions of bandwidth, cache size, propagation delay, content popularity and other factors. Then we specifically analyze the typical linear topology and the tree topology. Different from existing work, our model counts the complete delay including the queuing delay and the propagation delay in all links along the path, which makes it more accurate and practical.

The contributions of this paper mainly include the following aspects.

(1) We introduce the Markovian Queuing System theory into the ICN modeling. We adopt the Queuing theory to analyze the queuing delay which is a key part of the content delivery time. As far as we know, we are the first to introduce the Queuing theory to make complete analysis on the content delivery performance of ICN.
(2) We develop an analytical model for content transfer performance in ICN. We derive specific quantitative expressions for the average content delivery time as functions of its influencing factors. Moreover, we analyze some typical scenarios in the linear topology and the tree topology. Different from existing work, our model counts the complete delay including the queuing delay and the propagation delay in all links along the path, instead of only the forwarding delay at the bottleneck link.
(3) We verify the theoretic model by simulations and numerical analysis. The consistency between the simulation results and the numerical results has verified the accuracy of our model. We also evaluate our model by comparing with another typical model. The results illustrate that our model is more accurate.

The rest of this paper is organized as follows. For the convenience of understanding the model, the system description is firstly provided in Section 2. Then, Section 3 introduces the related work on the ICN modeling. Section 4 gives the main modeling assumptions and the main analytical results about the content delivery time. In Section 5 and Section 6, we report specific analytical and simulation results on linear topology and tree topology respectively. Section 7 discusses future research directions. Finally, Section 8 concludes the paper.

2. System description

For the convenience of description, analysis and simulation, we focus on the Named Data Networking (NDN) [9,10], which is a typical and specific ICN architecture in this study. Our model can also be applied or referred to other ICN architectures. We first give a brief description on how such systems work.

NDN defines two basic types of packets: Data and Interest. Content items are permanently stored in the repository (provider) and partly cached in the intermediate nodes. A content item is split into a sequence of Data packets uniquely identified by names. Each consumer implements a receiver-driven transport protocol to retrieve content by sending Interest requests. A name-based routing protocol guarantees the Interests are routed toward the data repository. Every intermediate node keeps track of pending Interests, in order to deliver the requested Data packets back to the receiver through the reverse path of Interests. Each router is equipped with a local cache that stores Data packets in order to satisfy future Interests for the same Data. In addition, intermediate nodes perform Interests aggregation to avoid forwarding multiple Interests for the same Data while the first one is pending.

Data may come from the original repository or from any hitting cache, that is a cache with a temporary copy of the data packet, along the path toward the original repository (a machine that permanently stores the whole catalog of content objects). Therefore, data of the same content can be retrieved from multiple sources/locations with different round trip times (RTTs), which affects the delivery performance. The resulting content delivery time is strongly affected by the average distance between the consumer and the data source, which we will define as *virtual round trip time* (VRTT) in analogy with connection-based transport protocols like TCP.

In this paper, we mainly focus on the expected content delivery time as a main performance metric. Without loss of generality, we use simple network topologies including line and tree topologies. The framework can be extended to wider topologies.

3. Related work

ICN has become a hot research topic in the field of future generation Internet [5]. As a new architecture, on one hand, ICN has many advantages over the traditional TCP/IP architecture. On the other hand, ICN also has many research challenges to be solved [11], such as the specific architecture, naming, routing [12], transport [13], caching [14], mobility [15] and security [16].

At the aspect of transport, there are already many transport protocols proposed for NDN [13], such as ICP [17]/HR-ICP [18], ICTP [19], HIS [20], CCTCP [21] and ECP [22]. However, there are few works on the transport model in NDN or ICN. Moreover, these protocols usually have not considered the in-network caching in their designs of congestion control algorithm, whereas the in-network caching is one of new features of ICN and has a significant influence on the content delivery performance. On the other hand, there are many works on the caching in ICN [14], mainly including cache deployment and sharing mechanism, cache decision policy, and cache replacement algorithm etc. However, there are relatively few works on the analytical modeling of ICN cache network. Moreover, there are few studies on the interaction with caching and transport in ICN, especially from the aspect of modeling.

In the context of Web caching, there have been some research on modeling content-level cache dynamics. Most of them consider LRU replacement policy. However, most of them only consider a single cache scenario, such as [23,24], and only few works consider a network of caches, such as [25]. Among these works, [26] studied the miss sequence of LRU cache replacement policy, and provides an analytical characterization of the miss probability and miss rate under Poisson assumptions of content requests' arrivals from the viewpoint of caching.

Recently, some works begin to model the caching performance in ICN, such as [27,28]. [27,29] extend the work in [26] and consider both the caching and transport. They not only analyze the miss probability, but also derive expressions for the average content delivery time. However, to compute the average content delivery