Computer Networks 78 (2015) 119–129

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

An energy-efficient distributed in-network caching scheme for green content-centric networks

Chao Fang [a,*], F. Richard Yu [b], Tao Huang [a], Jiang Liu [a], Yunjie Liu [a]

[a] *Key Lab. of Universal Wireless Comm., Ministry of Education, Beijing University of Posts and Telecom., Beijing, PR China*
[b] *Depart. of Systems and Computer Eng., Carleton University, Ottawa, ON, Canada*

A R T I C L E I N F O

Article history:
Received 27 February 2014
Received in revised form 29 August 2014
Accepted 22 September 2014
Available online 26 November 2014

Keywords:
In-network caching
Content-centric networking
Energy efficiency
Non-cooperative game

A B S T R A C T

Due to the in-network caching capability, Content-Centric Networking (CCN) has emerged as one of the most promising architectures for the diffusion of contents over the Internet. Most existing works on CCN focus on network resource utilization, and the energy consumption aspect is largely ignored. Moreover, the existing centralized schemes for CCN may not be practical to be implemented in realistic networks due to the distributed architecture of the Internet. In this paper, we propose an energy-efficient distributed in-network caching scheme for CCN. In the proposed scheme, each content router only needs locally available information to make caching decisions considering both caching energy consumption and transport energy consumption. We formulate the energy-efficient distributed in-network caching problem as a non-cooperative game. Through rigorous mathematical analysis, we prove that pure strategy Nash equilibria exist in the distributed solution, and it always has a strategy profile that implements the socially optimal configuration, even if the routers are self-interested in nature. Simulation results reveal that the proposed scheme is competitive to the centralized scheme, and has superior performance compared to the other widely used schemes in CCN. Besides, it exhibits a fast convergence speed when the capacity of content routers varies.

1. Introduction

With the explosive growth of the Internet traffic caused by sharing user generated data (e.g., YouTube) and delivering multi-media content (e.g., Netflix), Internet communication pays more attention to the content itself rather than where it is physically located [1,2]. However, the current Internet, originally conceived to enable communication between machines, lacks natural support for content distribution. This fundamental mismatch has a significant impact on the network performance in terms of end user quality of experience, bandwidth costs, delay, and energy use [3,4].

Initial attempts to accommodate content distribution within the Internet infrastructure have resulted in a plethora of application-specific solutions, e.g., Content Delivery Networks (CDNs) (also referred to as Content Distribution Networks) [5] and Peer-to-Peer (P2P) networks, which have bulit-in large-scale and distributed caching mechanisms. However, content caching is only deployed as an overlay service rather than an inherent network capability. Due to the lack of storage capability at individual routers, these caching mechanisms lead to suboptimal utilization of network resources [6].

Recently, as a potential solution to these limitations, Content-Centric Networking (CCN) [3,7] has emerged as one of the most promising architectures for the diffusion of contents over the Internet. A major feature of this novel networking paradigm is in-network caching [8–10]. In

* Corresponding author. Tel.: +86 15117931239.
E-mail address: fangchao.bupt@gmail.com (C. Fang).

http://dx.doi.org/10.1016/j.comnet.2014.09.017
1389-1286/

CCN, each content router has caching capability, which can cache content objects to shorten the distance of user requests.

Although some excellent works have been done on CCN, most of them focus on the performance improvement of network resource utilization [4]. Consequently, the energy consumption aspect in this setting is largely ignored [11]. However, the increasingly rigid environmental standards and rapidly rising energy costs have led to an emerging trend of addressing "energy efficiency" aspect of the Internet. Indeed, the energy consumption of the Internet is estimated to account for up to 10% worldwide energy consumption and keeps constantly increasing [12]. The authors of [13,14] make fine attempts in considering energy efficiency of CCN. However, the schemes proposed in [13,14] are centralized schemes to minimize the global network energy, which may not be practical to be implemented in realistic networks due to the distributed architecture of the Internet [15]. Particularly, in multiple Internet service providers (ISPs) environment, it is difficult to have a centralized administration to coordinate content routers that belong to different ISPs.

In this paper, we propose an energy-efficient distributed in-network caching scheme for CCN. The distinct features of this paper are as follows.

- In the proposed energy-efficient distributed in-network caching scheme, each content router only needs locally available information to make caching decisions considering both caching energy consumption and transport energy consumption.
- We formulate the energy-efficient distributed in-network caching problem as a non-cooperative game [16]. Through rigorous mathematical analysis, we prove that pure strategy Nash equilibria exist in the distributed solution, and it always has a strategy profile that implements the socially optimal configuration, even if the routers are self-interested in nature.
- We evaluate the proposed distributed scheme in heterogeneous network conditions and compare it with a centralized scheme and other common techniques widely used in CCN, such as Leave Copy Everywhere (LCE), FIX(P), Random Caching (RND) and Unique Caching (UniCache) [17,18] using GT-ITM [19] and Inet [20] network topology generators. Simulation results reveal that the proposed scheme is competitive to the centralized scheme, and has superior performance compared to the other widely used schemes in CCN. Besides, it exhibits a fast convergence speed when the capacity of content routers varies.

The rest of this paper is organized as follows. In Section 2, some important background information related to replica placement problem is introduced. In Section 3, the system model is given. In Section 4, the problem to resolve is formulated, and the centralized solution is presented. In Section 5, the distributed solution based on non-cooperative game is presented. Simulation results are presented and discussed in Section 6. Finally, we conclude this study in Section 7.

2. Related work

The placement of content replicas is one of the most important issues in the caching problem for content distribution. A substantial amount of research has been devoted to the content placement problem in CDNs, where the objective is to find the number of content copies and their locations in network to minimize a cost function that typically captures access costs (delay, bandwidth), and/or storage costs (cost of placing and/or keeping an object), subject to storage capacity constraints [21–24]. The content placement problem can be formulated as a mixed integer linear program (MILP), which is shown to be NP-Hard [21]. Tractable solutions have been proposed in the form of approximation algorithms based on greedy algorithms [21,22], or LP relaxation techniques [23,24], where equal size objects, network symmetry, and hierarchical structures, are usually assumed.

Our work on CCN is different from these CDNs-based works, since they do not consider in-network caching of CCN and need the above strict assumptions. The main idea of CDN is to have the most popular contents available in those nodes that can provide a shorter response time since they are closer to the end users. The dominant CDN players (e.g., Akamai and Limelight) are not network operators but third-party providers, which deploy their CDN infrastructure outside a network operator's network as an overlay network. CDNs lead to costly and/or inefficient solutions for content distribution [25]. In CCN, however, nodes in the path can cache and forward content to subsequent end users requesting the same contents. Then for popular contents, several end users in the same network vicinity can request the same content, and the CCN node can deliver it by itself, if it has it in cache. With CCN, the benefit of cache function in the network applies at many levels, enabling the network load to be greatly reduced, starting from the operator network [25]. In essence, CCN promotes content, which is already an explicit application-layer element, to an explicit network-layer entity as well, thereby requiring the application to only maintain knowledge that does not deviate from its own traditional knowledge base [26].

Compared to a large body of research on traditional Internet caching, CCN in-network caching is relatively new. Luca Muscariello et al. propose an analytical framework for the performance evaluation of content delivery under the limited resources of statistical bandwidth and sharing storage [27]. Caching trees of CCN are studied in [27], which mainly focuses on the theoretical analysis. An analytical tool is proposed in [28] for the approximation of cache content distribution and hit-ratio for any multi-cache topology and for any Least Recently/Frequently Used (LRFU) caching policies based on both recency and frequency. Psaras et al. present a probabilistic caching algorithm in [29]. An effective caching scheme is proposed in [30] to draw content replicas closer to the requesters.

Although these excellent works exploit the in-network caching capability in CCN, the energy efficiency issue is largely ignored. Initial assessment studies have shown that the additional energy consumption incurred by providing