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Angaben zur Veröffentlichung / Publication details:

Seufert, Michael, Valentin Burger, Florian Wamser, Phuoc Tran-Gia, Christian Moldovan, and Tobias Hoßfeld. 2015. "Utilizing home router caches to augment CDNs towards information-centric networking." In European Conference on Networks and Communications (EuCNC), June 29 - July 2, 2015, Paris, France, edited by Mario Campolargo and Nicolas Demassieux. Augsburg: Universität Augsburg.

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Utilizing Home Router Caches to Augment CDNs toward Information-Centric Networking

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***Abstract*—To implement improved Quality of Service (QoS) and Quality of Experience (QoE) management for content-heavy services like video streaming, content has to be moved closer to the edge. The concept of information-centric networking (ICN) would be a prospective enabler but is currently not practically feasible yet. We propose a hierarchical caching architecture utilizing caches on home routers to augment existing content delivery network (CDN) infrastructure. This approach can be implemented via Software-defined Networking (SDN) and brings current CDNs closer towards ICN. Based on a simulation study, we confirm that our approach is able to serve content more locally, which results in QoS and QoE benefits for end users as well as inter-domain traffic savings for network operators.**

I. Introduction

The importance of the Internet for social and economic ends has increased over the last years, especially due to the large market growth for smartphones and tablet computers. Further, Online social networks (OSN) like Facebook attract millions of users and connects them to each other. User activities in OSN such as micro-blogging (Twitter) and exchange of photos and videos (Facebook) are responsible for huge portions of the overall Internet traffic. This overlay traffic generated by OSNs implies congestion increase within networks of ISPs as well as an increase of operating costs, especially for inter-domain traffic. In contrast, the mechanisms used for traffic management in the Internet are still based on concepts unchanged since its initial inception and cannot cope with the increasing requirements of users, network operators and service providers. One approach to dealing with the growing Internet traffic while satisfying its requirements is Information-Centric Networking (ICN).

One important example for such a requirement is the Quality of Experience (QoE) perceived by the user and economic considerations of the service providers. QoE is particularly important in video traffic which is often induced by OSN, e.g., if a user posts a link to a video served by a CDN and recommends this video to his friends within the OSN. Using social-aware mechanisms for caching or prefetching, QoS and QoE can be improved. When we look at efficient transmission of video content, the QoE and the costs for the network operators need to be considered. However, not only network operators, but also content providers, video platforms and users are interested in improving QoS and QoE. In order to achieve this, the content needs to be brought closer to the edge. These issues lead us to some fundamental research questions that can be formulated as follows: *Can we build an ICN-based architecture to improve QoS and QoE? Is this possible through integration with an existing architecture? How does such an architecture perform? What limitations do exist?*

While there are no satisfying practical implementations for ICN, we intend to use home router gateways as caching infrastructure as presented in HORST [1]. We further propose a tiered caching architecture that connects home router caches with the existing CDN infrastructure. In addition this architecture makes use of the owners's OSN profile in order to optimize the efficiency of the cache. In order to realize traffic and resource management across home routers, the home routers may be controlled through Software-defined networking (SDN) with a centralized view on the network, e.g. to prevent congestion degrading QoE. We evaluate the performance of the proposed architecture in a simulation. The results of the simulation indicate that QoS can be increased quantitatively in terms of cache hit ratio. Since this may lead to bottlenecks being overcome due to shorter paths, higher QoE can be expected.

The remainder of the paper is structured as follows. Section II gives background on Internet video delivery and Information-Centric Networking. In Section III we describe the proposed architecture. This architecture is evaluated numerically in Section IV. The paper is finally concluded in Section V with a discussion on relevant future work.

II. Background

A. Internet Video Delivery

HTTP video streaming is a combination of video download and concurrent playback. As the network conditions are fluctuating, delays can be introduced at the application layer due to the TCP transmission. These delays (initial delay, stalling/rebuffering) are the key influence factors of video streaming QoE [2], [3]. Recently, HTTP Adaptive Streaming (HAS) was developed, which allows for a flexible adaptation of the video quality to the available network resources and device capabilities. The video is split into small chunks of a few seconds of playtime and stored in multiple bit rates. Clients request the next chunks in an appropriate bit rate based on own network measurements in order to best utilize the available bandwidth while avoiding stalling to the greatest extent. Although, changing the transmitted video quality as employed by HTTP adaptive streaming generally improves QoE compared to classical video streaming [4], adaptation has a significant impact on QoE [5]. The HAS streaming technology is adopted by many applications and video content providers [6] and is standardized in ISO/IEC 23009-1 [7].

The appearance of dynamic services and the increasing quality of multimedia content raised user expectations and the demand on the servers. To bring content in high quality to end-users with low latency and to deal with increasing demand, content providers have to replicate and distribute the content to get it close to end-users. In today's Internet, Content Distribution Networks (CDNs) provide the basic infrastructure and technology and are widely used for the delivery of content, such as videos [8].

In a CDN, data centers are set up across the globe and interconnected to important edge points of presence. As this allows for peering links between the CDN and access networks with many end users, access network providers save transit costs and content can be accessed with low latency. To bring content even closer to users, ISPs can deploy CDN servers inside their own network to serve popular content, e.g., [9]. CDNs utilize the Domian Name System (DNS) to select the closest server for a content request. The last DNS resolution can happen repeatedly until a content server is found, which has enough capacity to serve the request. Thus, load balancing between the servers is achieved [10]. Being the most important video CDN, the structure the YouTube CDN is analyzed in [11], [12], while [13] takes a look at it from an end user perspective.

B. *Information Centric Networking*

The basic concept of Information Centric Networking (ICN) is the addressing of content instead of a physical server. This allows to store a content in different locations (caches) in the Internet. The most important question is where to store which content in order to optimally utilize the available resources, to maximize the end users' QoE, and to minimize the costs for ISPs and providers of content-heavy services such as video streaming.

ICN has similar goals as CDN and peer-to-peer (P2P) mechanisms, which are well established technologies, and brings together different aspects from both worlds. Table I compares the three concepts with respect to infrastructure, cache location, and deployment. The main difference of ICN and CDN is that not only servers in data centers but all network devices can serve as caches. However, the ongoing standardization limits the immediate operation of ICN mechanisms. P2P, on the other hand, is also a highly distributed concept, but completely based in the end users' premises. Thus, advantages of large operators like economies of scale, which can be exploited with ICN, are not available for P2P mechanisms.

[14] investigates a two tiered video caching architecture consisting of home routers in access networks and data center caches in the core network. Content requests are independent and identically distributed and the popularity of videos follows a power law (Zipf law) [15], [16]. The Least Recently Used (LRU) caching strategy is modeled in [17], [18]. Other caching strategies like Sliding Window for Least Frequently Used (W-LFU) and Geometrical Fading are investigated in [19]. Popularity-based caching, e.g., Popularity-Based Least-Recently Used (PBLRU) [20] decides to cache based on the popularity of content by exponential moving average over time of the content's popularity. Edge caching is described in [21], which regards the content source as the root and consumers as leafs of a tree. Content is stored close to the customers at the leaf nodes, i.e., the last nodes on a delivery path. [22] uses a hierarchical ICN architecture to cache globally popular contents and contents popular in social groups.

TABLE I. COMPARISON OF CDN, ICN, AND P2P.

Feature	CDN	ICN	P2P
Infrastructure Owner	CDN operator	Cloud/network operators	End users
Cache location	Data centers	Network devices	End users
Deployment	Proprietary	Ongoing standardization	Open source/proprietary

Software-defined networking (SDN) is a promising solution to realize the ICN concept in existing IP networks [23], [24], [25]. The principles of SDN include decoupling the control plane and the forwarding plane of a network, programmability, and logical centralization of the network control plane. The centralized view and central state information of the SDN controller may be useful to enable easier path selections in ICN and to locate resources and contents at various network entities (caches, home gateways by end users, CDNs, etc.). SDN testbeds for ICN, which are realized with OpenFlow, are described in [26], [27], [28] and show the feasibility of this approach.

III. INTEGRATION OF HOME ROUTER CACHES FOR IMPROVED QOS MANAGEMENT

A. *Basic Concept*

Information-centric networking is widely considered a beneficial concept, which will implicitly improve QoE by inherent caching mechanisms. However, due to the lack of standardization, practical implementations cannot be expected in the near future. Despite this issue, we propose a more practical approach, which aims to bring the CDN concept closer to ICN by utilizing home routers. This approach combines the best of both CDN and P2P worlds, which include a high content distribution among many caches as well as powerful operator caches.

HORST [1] is a socially-aware traffic management solution, which allows to share WiFi access among trusted users. Moreover, it utilizes home routers to cache and prefetch videos based on information from the owner's OSN profile and interconnects all participating home routers in a P2P fashion to establish an efficient content distribution overlay. Thus, it allows end users to participate in the content distribution by

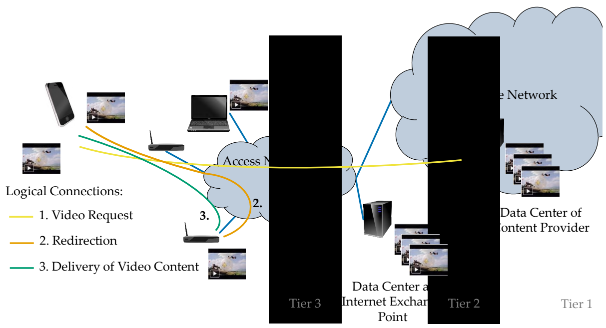

Fig. 1. Caching of video contents at different locations and tiers.

TABLE II. DEFAULT PARAMETERS OF THE CONTENT DELIVERY SIMULATION FRAMEWORK.

Parameter	Default value	Description
N	100000	Catalogue size in number of items
C_{ISP}	$0.01 \cdot N$	ISP cache capacity
$strat_{ISP}$	LRU	Caching strategy of ISP caches
C_{HR}	4	Home router cache capacity in number of items
$strat_{HR}$	LRU	Caching strategy for home routers
p_{share}	10^{-4}	Home router share rate
	Leave-copy-down	Hierarchic caching strategy
$n_{requests}$	10000	Number of requests
α	0.99	Exponent of Zipf content popularity
n_{user}	1829425	Number of users / home router
n_{AS}	100	Number of autonomous systems

sharing the caching resources of their home routers. The content distribution and request redirection can be implemented using SDN. Additionally, an SDN controller may implement traffic engineering, e.g., at home routers, in order to control the network utilization and to achieve high QoE for all users.

Together with existing CDN infrastructure, i.e., caches deployed by CDN operators or ISPs, a tiered caching architecture can be established. Figure 1 depicts the scenario, which is considered in this work, for an adaptive video streaming service. The video content is available at different locations and in different quality levels. Tier-1 of the caching architecture consists of the data centers of the content providers in the core network. These large data centers contain all content items and can ultimately serve each end user request. Tier-2 resources are edge caches and ISP caches typically organized in a CDN, which are located close to Internet exchange points or in ISP networks. Requests served by ISP or edge caches produce less or no inter-domain costs. We will refer to these caches in the following as ISP caches. Tier-3 is located in the end users' premises and contains the caches on shared home routers that have the HORST firmware installed. We will refer to these caches in the following as home routers. Note that not all home routers participate in HORST and share their caching capabilities for content distribution.

In the proposed caching architecture, a request by an end user to a certain video content will be redirected to the closest cache with the goal of improving QoS and QoE for end users and saving inter-domain traffic for ISPs. In the following, we will assess the performance of the proposed approach through a simulation framework.

B. Simulation Framework

We evaluate a tiered caching architecture with resource locations at three different tiers, including the main data center of the content provider, content delivery network (CDN) caches, and end user equipment. Table II shows the default parameters of the content delivery simulation. The number of different content items that can be downloaded or streamed from the resources is specified by the catalogue size N. Tier-1 resource is the data center of the content provider, where all N content items are stored. The capacity of ISP caches is specified by C_{ISP}, the caching strategy of ISP caches is LRU. Each autonomous system hosts an ISP cache. The capacity of home routers is 4 content items and their caching strategy is LRU. 1829425 home routers are distributed among 100 autonomous systems according to a power law with slope 1.5. The probability that a user has HORST installed and shares his home router for content delivery is given by p_{share}. The probability that a user requests certain content items depends on the content popularity distribution, which is specified by the Zipf exponent α. A requested item is first looked up in the home router of the user, if it is not found, it is looked up in tier-3 caches in the same autonomous system then in tier-2 caches, and finally, in the data center of the content provider. The hierarchic caching strategy is leave-copy-down, which means that the video is cached in a certain tier only if it is already available in a higher tier.

The content delivery simulation framework is implemented in Matlab. The simulation is event-based using watch events, which are processed when a user watches or consumes a video item. The process of a watch event starts by selecting a video dependent on the demand model specified in the parameters. A video with video identifier vid is returned. In the next step a cache or data center is selected that holds the item with vid. The download of the item from this resource is recorded in the statistics. The cache identifier cid is returned and the cached items are updated according to the caching strategy specified in the parameters.

IV. Numerical Results

In the following, we evaluate the performance of the tiered caching architecture. By studying the impact of the home router sharing probability, we identify the amount of home routers, which needs to be shared so that such a mechanism pays off for ISPs. We vary the ISP cache capacity to investigate to what extent the load on ISP caches can be reduced. For each configuration, 5 simulation runs were conducted to achieve significance. The results show the mean value of the 5 runs with 95% confidence intervals.

Figure 2 shows the ISP cache contribution depending on the home router sharing probability for different cache capacities. The ISP cache contribution is the share of requests served by ISP caches. The ISP cache contribution decreases with the home router sharing probability. This depends on the fact that more requests are served from home routers with increasing home router sharing probability. The ISP cache

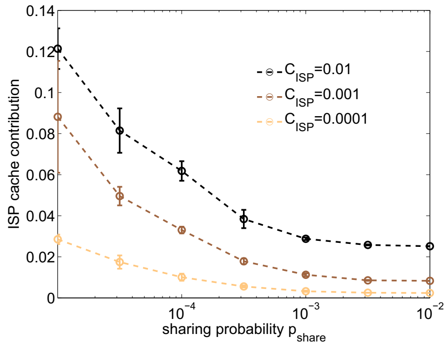

Fig. 2. Share of requests served by ISP caches depending on home router sharing probability for different ISP cache capacities.

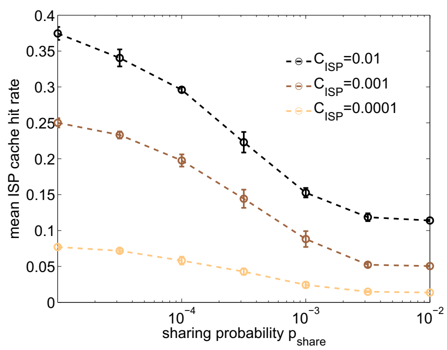

Fig. 3. Mean ISP cache hit rate depending on home router sharing probability for different ISP cache capacities.

contribution also decreases with the ISP cache capacity, which is clear because less content items can be stored on ISP caches, which decreases the probability that a request can be served by an ISP cache. The ISP cache capacity has more influence on the total ISP cache contribution for low sharing probabilities. Hence, especially if the home router sharing probability is low, a larger ISP cache capacity pays off.

Figure 3 shows the mean ISP cache hit rate in the evaluated scenario. It is obvious that the mean ISP cache hit rate decreases with the ISP cache capacity because the probability that a requested item is in the cache depends on the number of items stored in the cache. However, it is interesting that, for a constant ISP cache capacity, the mean ISP cache hit rate also decreases with the home router sharing probability. This depends on the fact that the ISP cache is only requested if an item is not found in a lower tier cache. The total cache capacity of home routers grows with the sharing probability, so that the ISP cache is only requested for rare or emerging new items. The probability that the unpopular items are located in the ISP cache is relatively low itself, which explains the bad ISP cache hit rate. This suggests using a different caching strategy at ISP caches to store especially rare and emerging items in the cache. Here, social information could also help to identify emerging items in advance and to store them on the ISP cache before they are requested frequently.

To investigate how much inter-domain traffic can be saved

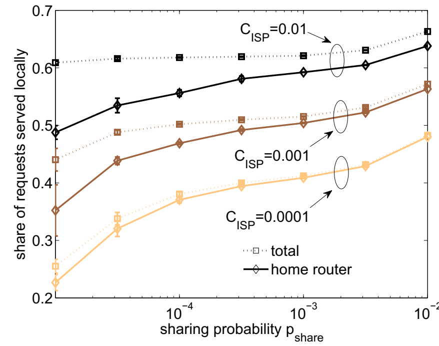

Fig. 4. Share of requests served intra-AS depending on home router sharing probability for different ISP cache capacities.

by the tiered caching architecture, we determine the requests that can be served locally. Additionally, locally served traffic implies a high QoS and QoE for end users. It has to be noted that future work is needed to quantify the improvement based on the simulation results. Figure 4 shows the share of requests served within an AS depending on the home router sharing probability for different ISP cache capacities. For low ISP cache capacities, the home router sharing probability has a high impact on inter-AS traffic. This depends on the fact that the ISP cache contributes less to the total autonomous system cache capacity. For higher ISP cache capacities, the share of requests served locally is less dependent on the home router sharing probability because the ISP cache can absorb more requests, which could not be served by home routers in tier-3. Hence, a high home router sharing probability is especially important for ISPs with small managed caches to save inter-domain traffic. If the ISP cache capacity holds one percent of the video catalogue size, more than 60% of requests can be kept locally independent of the home router sharing probability.

V. Conclusion

In this paper, we proposed a socially-aware architecture that uses home routers as caches and integrates them into the existing CDN infrastructure in order to improve QoS and QoE. Thereby, we come closer towards the ICN concept by caching contents in the network, on the path between source and consumer. Such a tiered caching architecture can be realized by integrating home gateways, for example, with HORST. This is even more appealing as an implementation of this ICN-related approach, which consists of CDN infrastructure and HORST, is possible with SDN. The results of the content delivery simulation framework show that this architecture has a high potential to save expensive inter-domain traffic, to take load from ISP caches, and to improve QoS and QoE for end users by serving content more locally. However, the results also show that the potential of the caching system is highly depending on the home router sharing probability. It might also depend on the popularity distribution of the content catalogue, which will be investigated in future work. This also includes to evaluate the performance of the caching architecture for content request patterns that exhibit social and temporal locality, which are typically observed for content shared via OSNs. Further, incentives to participate in this system need to be identified. Future work must also investigate mechanisms that ensure that all participants can be trusted. Finally, the performance of advanced caching and prefetching strategies, which also utilize social information, has to be evaluated.

ACKNOWLEDGMENT

This work was supported by by the Deutsche Forschungsgemeinschaft (DFG) under Grants HO4770/1-2 and TR257/31-2 (DFG project OekoNet) and in the framework of the EU ICT Projects SmartenIT (FP7-2012-ICT-317846) and INPUT (H2020-2014-ICT-644672).

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