A Survey of Energy-Efficient Caching in Information-Centric Networking

Chao Fang, F. Richard Yu, Tao Huang, Jiang Liu, and Yunjie Liu

ABSTRACT

To better cope with the Internet usage shift from host-centric end-to-end communication to receiver-driven content retrieval, innovative information-centric networking (ICN) architectures have been proposed. A notable advantage of these novel networking architectures is to provide transparent and ubiquitous in-network caching to speed up content distribution and improve network resource utilization. With the explosive increase of global network traffic, the energy efficiency issue in ICN is a growing concern. In this article, we provide a brief survey of energy-efficient caching techniques in ICN from the placement, content placement, and request-to-cache routing perspectives. We also outline some challenges and future research directions about caching policies for green ICN.

INTRODUCTION

According to the Cisco Visual Networking Index 2013, global IP traffic has increased more than fourfold in the past five years, and will grow threefold by 2017, to reach 120.6 exabytes per month. Most of the traffic can be attributed to the emergence of video streaming portals for user generated content (e.g., YouTube and Google Video) and video on demand (e.g., NetFlix, Hulu, and IPTV services). It is predicted that global consumer Internet video traffic will be 69 percent of all consumer Internet traffic in 2017, up from 57 percent in 2012, and the sum of all forms of video (e.g., TV, VoD, Internet, and P2P) will be in the range of 80–90 percent of global IP traffic by 2017. While IP has exceeded all expectations for facilitating ubiquitous interconnectivity, it was designed for conversations between communications endpoints, but is overwhelmingly used for content distribution. That is, today's Internet is increasingly used for information dissemination rather than pair-wise communications between end hosts [1], and pays more attention to the content itself rather than where it is physically located [2]. However, the current Internet, originally conceived to enable communication between machines, lacks natural support for content distribution. This fundamental mismatch has significant impacts on network performance in terms of end-user quality of experience, bandwidth costs, delay, and energy use [3].

Initial attempts to accommodate content distribution within the Internet infrastructure have resulted in a plethora of content-oriented applications/services, such as peer-to-peer (P2P) networks (e.g., Gnutella and BitTorrent) and content delivery networks (CDNs). In these application-/service-specific solutions, an end user does not care about hosts, but about content. Therefore, these mechanisms can improve content access and quality of user experience over the Internet. However, from a networking perspective, they still rely on a host-to-host communication model and do not take into account social semantics of transferred content for optimizing content routing or caching, which leads to costly and/or inefficient solutions for content distribution [4].

To better cope with the Internet usage shift from a sender-driven end-to-end communication paradigm to a receiver-driven content retrieval one, a handful of innovative information-centric networking (ICN) architectures have been proposed [1]. The philosophy behind ICN is to promote content to a first-class citizen in the network. In ICN, users do not care where the content comes from, but are only interested in what the content is. The essence of ICN lies in decoupling contents from hosts (or their locations) not at the application level, but at the network level. A notable advantage of these novel networking architectures is to provide transparent and ubiquitous in-network *caching* to speed up content distribution and improve network resource utilization, as requests no longer need to travel to the content source, but are typically served by a closer ICN content router along the routing path [5].

Although some excellent works have been done on ICN in-network caching, their focus is to increase cache hit rate and/or decrease network delay. Consequently, the energy consumption aspect in this setting is largely ignored [6]. However, the increasingly strict environmental standards and rapidly rising energy costs have led to an emerging trend of addressing the energy efficiency of the Internet. The information and communication technologies (ICT) sector is

Chao Fang, Tao Huang, Jiang Liu, and Yunjie Liu ,are with Beijing University of Posts and Telecom.

F. Richard Yu is with Carleton University.

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currently responsible for almost 2 percent of world electricity use in 2007, having observed an annual increase of 10 percent from 2007 to 2012. The total global electricity and diesel energy consumption by all mobile networks was approximately 120 TWh in 2010, resulting in energy costs of US$13 billion and responsible for 70 Mt carbon dioxide equivalent (CO_{2e}). In a business as usual (BAU) scenario, the non-negligible greenhouse gas (GHG) emissions of the ICT sector are expected to reach 1.43 Gtons CO_{2e} in 2020.

In this article, we provide a brief survey of energy-efficient caching techniques in ICN. The rest of this article is organized as follows. We first present the history and main components of ICN, and then introduce the architecture and workflow of the typical content-centric networking-based ICN approach. After introducing the ICN paradigm, we describe ICN in-network caching. We then present the existing energy-efficient techniques from the cache placement, content placement, and request-to-cache routing perspectives. We also outline some research challenges and future research directions for energy-efficient ICN caching. Finally, we conclude the article.

An Overview of Information-Centric Networking

This section introduces the history and main components of ICN, and presents the architecture and workflow of the typical content-centric networking-based ICN approach.

A Brief History of Information-Centric Networking

ICN has been attracting increasing attention from both academia and industry. A number of ICN initiatives focus on designing an Internet architecture that can replace the current host-centric model and directly address the content delivery problem described above. The concept of ICN dates back to 1999, when Cheriton *et al.* introduced the concept of name-based routing in translating relaying Internet architecture integrating active directories (TRIAD), which proposed to avoid DNS lookups by using the name of an object to route toward a close replica of it. In 2007, data-oriented network architecture (DONA) was proposed as one of the first clean-slate ICN proposals. DONA uses flat, self-identifying, and unique names for information objects, and binds the act of resolving requests for information to locating and retrieving information, which improves TRIAD by incorporating security (authenticity) and persistence as first-class primitives in the architecture.

Subsequently, a number of research efforts have been dedicated to ICN, including the EU funded projects Publish-Subscribe Internet Technology (PURSUIT) and its predecessor Publish-Subscribe Internet Routing Paradigm (PSIRP), Scalable & Adaptive Internet Solutions (SAIL) and its predecessor 4WARD, Content Mediator Architecture for Content-Aware Networks (COMET), CONVERGENCE, the U.S. funded projects Named Data Networking (NDN) and its predecessor Content-Centric Networking (CCN) and MobilityFirst, the French funded project ANR Connect, which adopts the NDN architecture, as well as the collaborative EU-Japan project called GreenICN.

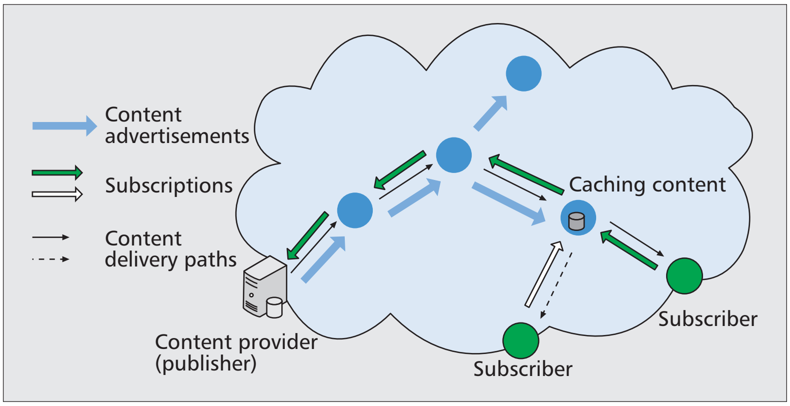

Figure 1. An information-centric network.

The Main Components of Information-Centric Networking

The communication paradigm within ICN is different from that of IP. Current IP architectures revolve around a host-based conversation model (i.e., a communication is established between two hosts before any content is transferred), and the delivery of data in the network follows a source-driven approach (i.e., the path is set up from the sender to the receiver). The principal concern of ICN is to disseminate, find, and deliver information rather than the reachability of end hosts and the maintenance of conversations between them. In ICN, the user requests content without knowledge of the host that can provide it, the communication follows a receiver-driven principle (i.e., the path is set up by the receiver to the provider), and the data follows the reverse path. The network is then in charge of doing the mapping between the requested content and where it can be found (Fig. 1). The match of requested content rather than the findability of the endpoint that provides it thus dictates the establishment of a communication in ICN.

To be efficient, one key aspect of ICN is naming. Content should be named in such a way as to be independent of the location of the node where the content can be found, which is the main objective of ICN (to separate naming and location). ICN also includes a native caching function in the network in such a way that nodes can cache the contents passing through it for a while (depending on the cache size and replacement algorithm) and deliver them to requesting users. Via this in-network caching mechanism, the content is replicated, and the delivery probability of the content to the end user is increased.

Decoupling naming from location also allows native support of mobility or multicast in ICN. Indeed, when users move, they are connected to another node in the ICN network, but since no IP address is used for the routing, it is transpar-

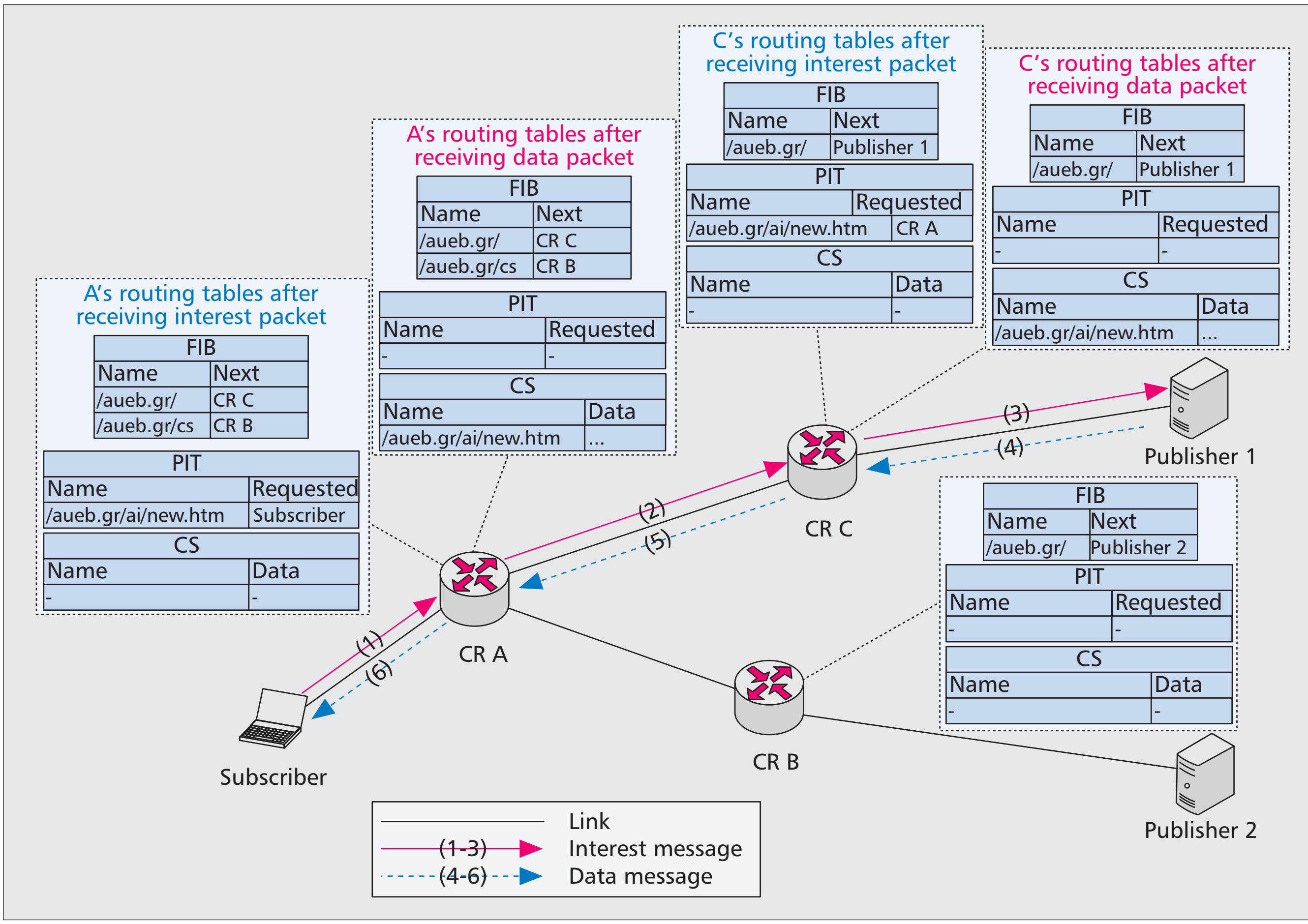

Figure 2. Content-centric networking-based ICN architecture. CR: content router; FIB: forwarding information base; PIT: pending interest table; CS: content store.

ent, as opposed to IP, where the address should be changed. For multicast, as soon as one user has requested a given content, one node can cache it and then deliver it for subsequent requests for the same content. It then naturally creates multicast-like content delivery.

Introduction to Content-Centric Networking: A Pioneer Information-Centric Networking Solution

The open source implementation of CCN describes a complete naming scheme, content retrieval storage, and dissemination algorithms, and this implementation is also the root of the NDN project proposing a comprehensive networking protocol designed around CCN. Consequently, CCN has become one of the most promising techniques for ICN [4, 7]. Therefore, in this subsection, we present the architecture and workflow of CCN-based ICN approach.

Architecture of Content-Centric Networking — The CCN-based ICN architecture is showed in Fig. 2. CCN is a receiver-driven data-centric communication protocol. Communication in CCN is performed using two distinct types of packets: *interest packets* and *data packets*. Both types of packets carry a name, which uniquely identifies a piece of data that can be carried in one data packet. Besides, to receive data, each CCN content router (CR) maintains three major data structures: a content store (CS) for temporary caching of received data packets, a pending interest table (PIT) to contain the names of interest packets and a set of interfaces from which the matching interest packets have been received, and a forwarding information base (FIB) to forward interest packets.

The Workflow of Content-Centric Networking — Figure 2 also shows the working procedure of the CCN-based ICN architecture. The subscriber sends an Interest for the name /aueb.gr/ai/new.htm (arrows 1–3). When the interest packet arrives, the CR extracts the information name and looks for an information object in its CS with a name matching the requested prefix. If something is found, it is immediately sent back through the incoming interface in a data message, and the interest packet is discarded. Otherwise, the router performs a longest prefix match on its FIB in order to decide in which direction this interest packet should be forwarded. If an entry is found in the FIB, the router records the interest packet's incoming interface in the PIT and pushes the packet to the CR indicated by the FIB.

When an information object that matches the requested name is found at a publisher node or a CS, the Interest message is discarded and the information is returned in a Data message. When a CR receives a Data message, it first stores the corresponding information object in its CS and then performs a longest-prefix match in its PIT to locate an entry matching the data packet; if a PIT entry lists multiple interfaces, the Data message is duplicated, thus achieving multicast delivery. Finally, the CR forwards the Data message to these interfaces and deletes the entry from the PIT (arrows 4–6). If there are no matching entries in the PIT, the router discards the data packet as a duplicate.

In-Network Caching of Information-Centric Networking

In this section, we first introduce the advantages of in-network caching in ICN, and then present two approaches to in-network caching.

Advantages of In-Network Caching

In-network caching is a fundamental feature of ICN architectures, as information awareness allows the network to identify cached information without resorting to the application layer, as in web caching. Therefore, it can improve network performance by fetching content from nodes geographically placed closer to the end user. An illustration of content caching in CCN is shown in Fig. 3. The usefulness of caching is already proven by the commercial success of CDNs. ICN generally leverages in-network storage to provide a better-performing and more robust transport service. For example, the advantages of in-network caching for an Internet service provider (ISP) may be twofold: reducing the incoming traffic from neighbor ISPs to lower the traffic load on its cross-ISP links (and hence its expense for transport link capacity) and improving the delay/throughput performance by placing the contents closer to their users. In-network caching is also attractive to content providers (CPs) since it can mitigate the capital expense of their content servers.

On-Path and Off-Path Caching

There are two approaches to in-network caching: on-path and off-path caching. On-path caching is generally opportunistic (i.e., routers cache information that happens to flow through them), while off-path caching can be used to actively replicate information, as in CDNs.

On-Path Caching — A straightforward approach to content placement is on-path placement of contents as they travel from source to destination. In on-path caching, when a router receives a request for a piece of information, it responds with a locally cached copy without involving the name resolution system. Although this approach reduces the computation and communication overhead of placing content within the network, it might reduce the chances of hitting cached contents.

An important issue in on-path caching is how each node makes a caching decision to improve the cache hit rate of content delivery. For example, popular content might need to be placed where it is going to be requested next. Furthermore, problems of expected content popularity or temporal locality need to be taken into account in designing in-network caching algorithms in order for some contents to be given priority (e.g., popular contents vs. one-timers). The criteria as to which contents should be given priority in in-network content caches also relate to the business relationships between content providers and network operators.

While all ICN architectures natively support on-path caching in principle, when name resolution and data routing are decoupled there are fewer opportunities to exploit opportunistic caching, as the name resolution path generally differs from the data routing path: while the information can be opportunistically cached on the data routing path, subsequent requests for the same information follow the (different) name resolution path, reducing the possibility for a cache hit. However, when name resolution and data routing are coupled, if data is cached on the data routing path it will result in a cache hit when subsequently requested over the same name resolution path. Opportunistic caching can range from the "cache everything" approach of CCN to the probabilistic caching approach of COMET [8].

Off-Path Caching — Off-path caching is similar to traditional proxy caching or CDN server placement. In off-path caching, caches announce

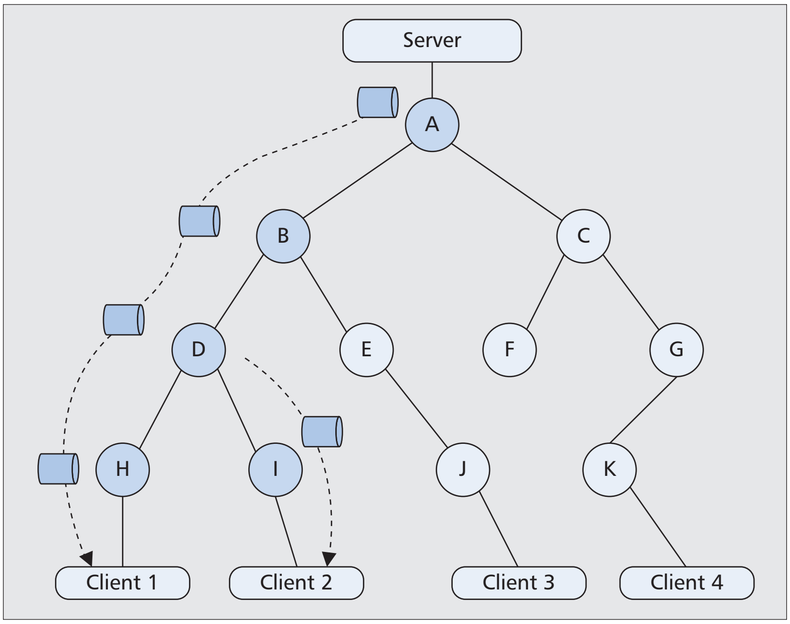

Figure 3. Illustration of content caching in CCN: Client 1 fetches a content by sending an interest packet. Initially, were no other interest packets were issued earlier, and intermediate ICN routers do not have the requested chunk in their buffers. The interest packet is eventually delivered to the origin server along the shortest path (i.e., H, D, B, and A). The requested chunk is then delivered by traversing the reverse path (i.e., A, B, D, and H), and each intermediate router keeps the forwarded chunk in its router buffer. If client 2 wants to access the same content, its interest packet will find a match at node D, and the requested chunk will be delivered directly from that node.

their information to the name resolution system so that they may be matched to information requests that would not normally reach them, essentially becoming alternative information publishers. Therefore, retrieval of contents from off-path caches requires redirection of requests.

Beyond the more general problem of choosing what to cache and where, the main issue in off-path caching is how to reduce the overhead required in order to inform the name resolution system when new items are cached or old items are discarded. The exact details depend on the name resolution scheme used, but one common goal is to keep updates local, for example, within an autonomous systems (AS) in order to reduce signaling overhead and only serve customers from within that AS [8]. In DONA and COMET, cached information can be advertised only within an AS and not propagated upward in the AS hierarchy (COMET provides the scope mechanism for this purpose). Similarly, in PURSUIT and the decoupled version of SAIL, cached information can only be advertised within the local distributed hash table (DHT) of an AS. In CCN, CONVERGENCE, and the coupled version of SAIL, the name prefix tables need to be updated, but it is unclear how this could be achieved economically as the routing protocols proposed for advertising name prefixes are based on flooding. MobilityFirst also faces problems in this area, as it relies on a global lookup mechanism for name resolution; therefore, it is unclear how locally cached copies can be advertised only within an AS.

Technology	Reference	Contributions
Energy-efficient cache placement	Braun *et al.* [6]	Analyzing the access frequency threshold from which caching content starts to be beneficial.
	Chen *et al.* [10]	Formulating the optimization of content router deployment as a convex optimization problem, and solving it by considering the trade-off between content router deployment cost and traffic transmission cost.
Energy-efficient content placement	Li *et al.* [11]	Establishing CCN energy consumption model, which relies largely on the average response hops of data dissemination.
	Choi *et al.* [12]	Considering different caching hardware technologies in CCN content router to reduce network energy consumption.
	Guan *et al.* [13]	Optimizing CCN content placement according to content popularity.
	Fang *et al.* [5]	Formulating energy consumption problem as a non-cooperative game, in which each content router makes local caching decisions considering both caching energy consumption and transport energy consumption.
	Llorca *et al.* [14]	Proposing an offline solution to maximize efficiency gains, and an distributed online solution to allow network nodes to make local caching decisions by estimating the current global energy benefit.
Energy-efficient request-to-cache routing	Kutscher *et al.* [9]	Proposing opportunistic caching and cache-aware routing techniques to gain the knowledge of a content's location.
	Sourlas *et al.* [15]	Proposing an intra-domain cache-aware routing scheme to minimize transportation cost based on the information item demands and the caching capabilities of the network.

Table 1. Energy-efficient caching techniques for information-centric networking.

Energy-Efficient Caching Techniques in Information-Centric Networking

Based on the analysis presented in the previous section, ICN in-network caching includes three important issues: cache placement (where is it best to put caches?), content placement (which content should go where?) and request-to-cache routing (how are cached content copies to be found?) [9]. For an ICN, the total consumed energy consists of two major parts: the transport energy and the caching energy. The transport energy includes the energy consumption in the core, edge, and access networks. The caching energy is consumed mainly by the contents cached in content routers, which obeys an energy-proportional model and depends on the caching hardware technology (e.g., SSD, DRAM, RLDRAM, SRAM, and TCAM). In this section, we give a summary of energy-efficient cache techniques in ICN from cache placement, content placement, and request-to-cache routing perspectives, which are presented in Table 1.

Energy-Efficient Cache Placement

ICN is a novel architecture that can be deployed to significantly reduce network capital cost at the lowest operating expense. The main hardware component of ICN is the content router with limited cache capacity. The position of ICN routers in a network has a direct influence on the overall performance. In this subsection, we address the practical issues regarding the possible deployment and evolution of ICN caches from an energy efficiency perspective.

Position of a Single Content Router — The position of a single router in ICN may have a significant impact on energy consumption. The further the content is cached from the user, the less duplication of content data is needed, and overall less storage energy is required. On the other hand, the closer the content is cached to the user, the faster the content can be served, and overall less transmission energy is required. For example, for different placement positions of the ICN router along the network described in Fig. 4, Braun *et al.* [6] analyze the access frequency threshold from which caching content starts to be beneficial.

Core and Edge Deployment — As shown in Fig. 5, the feasibility of deploying ICN in edge and core networks can be investigated from both the cost and energy perspectives. By considering various incremental deployment scenarios (both core and edge), ICN can outperform conventional CDNs and P2P networks under the considered scenarios. For instance, with 20 percent deployment of CCN routers in the cores, CCN can effectively reduce the hop length, thereby reducing energy consumption more than 15 percent [2].

The optimization of content router deployment in large-scale information-centric core-edge separation Internet can be solved by considering the trade-off between content router deployment cost and traffic transmission cost. Chen *et al.* [10] assume that content routers are deployed randomly with a certain probability, and formulate the optimization problem as a convex optimization problem. Then they find that the optimal deployment probability is affected by the average number of hops for reaching the content provider, additional cost for building a content router, and traffic transmission cost. Moreover, for given content router deployment cost and traffic transmission cost, the optimal deployment probability for most content providers remains within a small range. In fact, it is more effective to deploy ICN nodes at the edge. For example, the scenario with 20 percent deployment in the edge routers performs almost as well as the scenario with 100 percent deployment in the core [2]. A caveat of this result is that the total number of CCN routers will be much greater when deploying them in the edge, because the number of edge routers tends to grow exponentially.

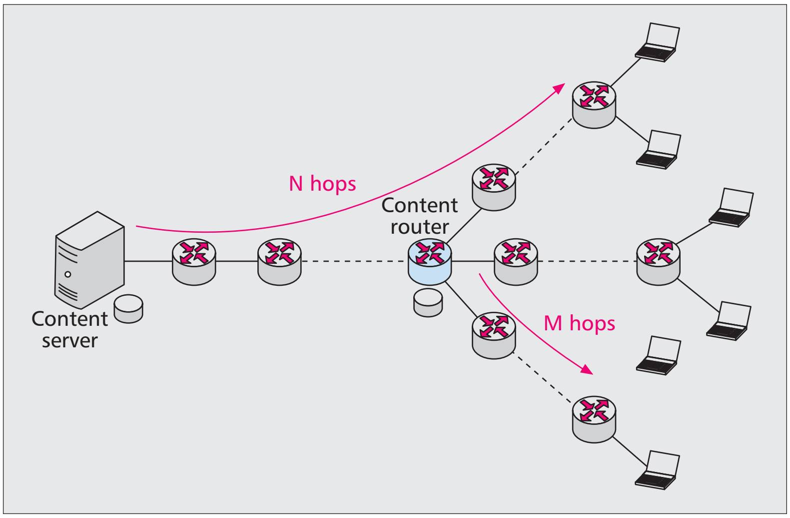

Figure 4. A network scenario of position of a single content router for ICN energy analysis.

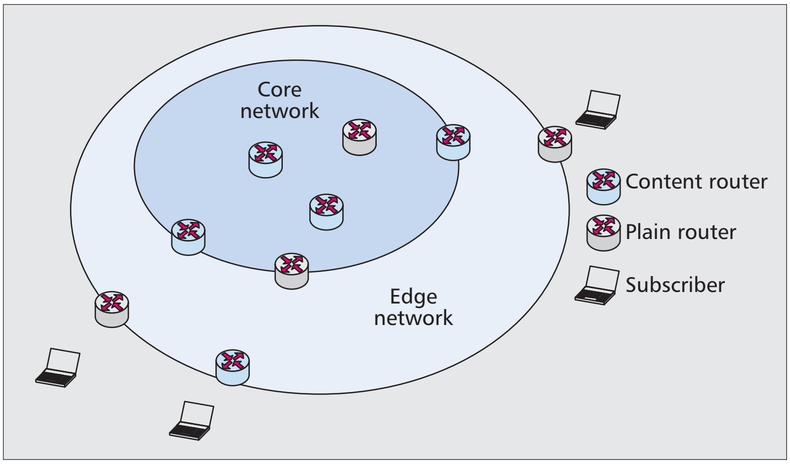

Figure 5. A network scenario of core and edge deployment for ICN energy analysis.

Energy-Efficient Content Placement — The placement of content replicas is another key issue for ICN in-network caching research. In an ICN network, content objects are dynamically created and requested, and can be cached as they travel toward end users, providing per-object-request granularity, responsiveness, and adaptation. The aim of the energy-efficient dynamic in-network caching problem is to find the evolution of the network configuration, in terms of the content objects being cached and transported over each network element at any given time, that meets user requests, satisfies network resource capacities, and minimizes overall energy use [14].

To maximize the energy saving, the energy optimization for ICN content delivery first needs to be designed. For example, an energy consumption model for CCN content delivery is studied in [11], where the energy consumption relies largely on the average response hops of data dissemination. Moreover, the authors of [12, 13] investigate the minimum energy consumption CCN can achieve with optimal content locations by considering different caching hardware technologies, number of downloads per hour, and content popularity. Although the optimization problem can be solved directly by solving in a centralized algorithm, all network information (e.g., the contents each node caches) in the network should be sent to a particular node to calculate the corresponding solutions, which should be distributed to the corresponding nodes in the network. Therefore, the centralized algorithm incurs huge communication overhead and lacks resilience to network changes.

To tackle the problem, the centralized energy consumption model can be transformed into a distributed one by adopting some proper tools. For instance, based on non-cooperative game, Fang *et al.* [5] propose an energy-efficient distributed in-network caching scheme to deal with the centralized energy consumption model for CCN, in which each content router only needs locally available information to make caching decisions considering both caching energy consumption and transport energy consumption. In addition, dual decomposition (DD) and the alternating direction method of multipliers (ADMM) methods can be considered. These transformed distributed energy consumption optimization algorithms can allow a global opti-

Object popularity is one of the major properties that affect cache efficiency. Research on current traffic patterns could shed additional light on the popularity characteristics of information today and thus benefit the design of energy-efficient caching schemes in ICN.

mization energy problem to be horizontally decomposed into parallel subproblems among the nodes.

To set the optimal solution as a benchmark, some distributed real-time caching policies based on network information (e.g., content popularity, user requests, equipment energy efficiency, and network topology) can also be designed to make a trade-off between the caching energy and the transport energy. For example, an efficient fully distributed online solution [14] is proposed to allow network nodes to make local caching decisions based on their current estimate of the global energy benefit.

ENERGY-EFFICIENT REQUEST-TO-CACHE ROUTING

In order to reduce energy consumption in ICN, requests have to be forwarded to the nodes that temporarily host (cache) the corresponding contents to take advantage of cached contents. This relates to energy-efficient request-to-cache routing, and the main challenge is that requests should ideally know the position of the cached content and follow the path to it. However, it is impractical to broadcast the instructions as to which content is cached where throughout the network. Therefore, the knowledge of a content's location at the time of the request might either not exist or be inaccurate (i.e., contents might have been removed by the time a request is redirected to a specific node).

To gain knowledge of a content's location, coordination between the data and control planes to update information of cached contents has been considered, but in this case scalability issues arise. There are two options to resolve the problem: opportunistic caching and cache-aware routing techniques [9]. In opportunistic caching, requests are forwarded to a server, and if the content is found on the path, the content is fetched from this node (instead of the original server). Cache-aware routing techniques can either involve both the control and data planes or only one of them. Furthermore, cache-aware routing can be done on a domain-wide scale or can involve more than an individual AS. For example, an intradomain cache-aware routing scheme is proposed to compute the paths with the minimum transportation cost based on information item demands and the caching capabilities of the network [15]. In the latter case, business relationships between ASs might need to be exploited in order to build a scalable model.

CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Although the caching technologies presented in the previous section can improve the energy efficiency of ICN, it is still a new research area full of challenges. There are a lot of issues that need to be addressed. In this section, we present some important yet challenging problems, and outline possible future research directions.

Chunk-Level Object Popularity — Object popularity is one of the major properties that affect cache efficiency. Research on current traffic patterns could shed additional light on the popularity characteristics of information today and thus benefit the design of energy-efficient caching schemes in ICN. In ICN, chunk-level object popularity rather than file-level object popularity should be considered. This line of study can be carried out in two directions. From the analytical point of view, the chunk-level object popularity model can be established from prior knowledge. These include established knowledge about file-level object popularity and distribution of object size, and reasonable assumptions on users' access behavior for chunks. From the experimental point of view, since currently there are no large-scale operational ICN network infrastructure and applications, it is difficult to measure the chunk-level object popularity directly. However, P2P systems, such as PPLive, can provide an opportunity to collect statistics about block-level object popularity. Certainly, the size of a block in P2P systems is different from the size of a chunk in ICN. However, their requesting behaviors are similar, so the results are analogous, and can be used at least as a reference for chunk-level object popularity in ICN.

Mix Traffic — Another issue is that when caching takes place in ICN, several types of traffic will compete for the same caching space. Therefore, cache space management becomes crucial for the network. Recent works, albeit based on simplified traffic models, have indicated that intelligent schemes can substantially improve energy efficiency in ICN. Although intelligent cache decision policies can reduce cache redundancy and increase the diversity of cached contents, making full use of content diversity needs complementary cache location mechanisms. How to devise and bundle low-complexity implicit cache decision policies and the corresponding intelligent cache location schemes in the face of the highly dynamic in-network cache environment remains an active research direction.

Wireless Information-Centric Networks — Mechanisms for energy-efficient caching have been studied mostly in the context of wired networks. With recent advances of wireless mobile communication technologies and devices, more and more end users access the Internet via mobile devices such as smart phones and tablets. This can create significant challenges in mobile environments, particularly mobile ad hoc networks (MANETs) and delay-tolerant networks (DTNs) due to the potential cost of managing cached replicas. Mobile node interests in content should be utilized to provide better network performance in terms of throughput, end-to-end delay, and energy consumption in both wireless and wired networks. Therefore, it is necessary to study the performance of existing energy-efficient caching techniques in ICN under wireless scenarios. Moreover, since currently there is no large-scale operational ICN network infrastructure and applications, large-scale tests on a real network (e.g., the PlanetLab environment) should be made to evaluate the actual effectiveness of these schemes under both wired and wireless scenarios.

Network Deployment — Another critical issue is that a sufficient number of content routers must be deployed throughout the network to reap the benefits of content caching. ICN can lower the energy consumption from the deployment and evolution perspective, but today's technology is not yet ready to support an Internet-scale CCN deployment. Nevertheless, by reducing the scope of a ICN deployment (i.e., from Internet scale to CDN or ISP scale), today's routers could easily be extended to become content routers. In this way, ICN can achieve energy efficiency while obviating the need to deploy preplanned and application-specific mechanisms, such as CDNs and P2P networks, which require sophisticated network services for mapping named content to hosts.

Although we consider equal deployment probability of content routers identified in the previous section, content routers can be deployed with various probabilities in different ASs. In addition, network topology, traffic flow, and the location of the content routers will also affect the traffic load of the information-centric core edge separation Internet. Therefore, it is interesting to investigate the optimization of content routers' deployment considering different deployment probabilities for core and edge network content routers. Moreover, investigating the deployment of content routers with consideration of the traffic flow and Internet topology is another research direction.

Since currently there is no large-scale operational ICN network infrastructure and applications, large scale tests on a real network (e.g. the PlanetLab environment) should be made to evaluate the actual effectiveness of these schemes under both wired and wireless scenarios.

Conclusions

Information-centric networking is a novel networking architecture and promotes content to a first-class citizen in the network. In this article, we present the history and main components of ICN, and then introduce the architecture and workflow of the typical content-centric-networking-based ICN approach. Next, we present the issue of ICN in-network caching, and review some existing energy-efficient caching techniques. Finally, we outline some challenges and future research directions about energy-efficient caching policies for green ICNs.

References

[1] A. Bianzino *et al.*, "A Survey of Green Networking Research," *Commun. Surveys and Tutorials*, vol. 14, no. 1, 2012, pp. 3–20.

[2] U. Lee, I. Rimac, and V. Hilt, "Greening the Internet with Content-Centric Networking," *Proc. 1st ACM Int'l Conf. Energy-Efficient Computing and Networking*, Passau, Germany, Apr. 2010.

[3] U. Lee *et al.*, "Toward Energy-Efficient Content Dissemination," *IEEE Network*, vol. 25, no. 2, Mar. 2011, pp. 14–19.

[4] B. Mathieu *et al.*, "Information-Centric Networking: A Natural Design for Social Network Applications," *IEEE Commun. Mag.*, vol. 50, no. 7, pp. 44–51, July 2012.

[5] C. Fang *et al.*, "Energy-Efficient Distributed In-Network Caching for Content-Centric Networks," *Proc. IEEE INFOCOM '14 Wksps.*, Toronto, Canada, May 2014.

[6] T. Braun and T. Trinh, "Energy Efficiency Issues in Information-Centric Networking," *Proc. Euro. Conf. Energy Efficiency in Large Scale Distrib. Sys.*, Vienna, Austria, Apr. 2013.

[7] B. Ahlgren *et al.*, "A Survey of Information-Centric Networking," *IEEE Commun. Mag.*, vol. 50, no. 7, July 2012, pp. 26–36.

[8] G. Xylomenos *et al.*, "A Survey of Information-Centric Networking Research," *Commun. Surveys Tuts.*, no. 99, July 2013, pp. 1–26.

[9] D. Kutscher *et al*, "ICN Research Challenges," IRTF, Internet Draft, draft-kutscher-icnrg-challenges-00, Feb. 2013.

[10] J. Chen *et al.*, "Optimizing Content Routers Deployment in Large-Scale Information Centric Core-Edge Separation Internet," *Int'l. J. Commun. Sys.*, vol. 27, no. 5, May. 2012, pp. 794–810.

[11] J. Li, B. Liu, and H. Wu, "Energy-Efficient In-Network Caching for Content-Centric Networking," *IEEE Commun. Letters*, vol. 17, no. 4, Apr. 2013, pp. 797–800.

[12] N. Cho *et al.*, "In-Network Caching Effect on Optimal Energy Consumption in Content-Centric Networking," *Proc. IEEE ICC '12*, Ottawa, Canada, June 2012.

[13] K. Guan *et al.*, "On the Energy Efficiency of Content Delivery Architectures," *Proc. IEEE ICC'11 Wksps.*, Kyoto, Japan, June 2011.

[14] J. Llorca *et al.*, "Dynamic In-Network Caching for Energy Efficient Content Delivery," *Proc. IEEE INFOCOM '13*, Turin, Italy, Apr. 2013.

[15] V. Sourlas, *Replication Management and Cache Aware Routing in Information-Centric Networking*, Ph.D. thesis, Dept. ECE,, Univ. Thessaly, Greece, July 2013.

Biographies

Chao Fang received his B.S degree in information engineering from Wuhan University of Technology, China, in 2009. He is currently working toward his Ph.D. degree at the State Key Laboratory of Networking and Switching Technology of Beijing University of Posts and Telecommunications (BUPT). Since August 2013 he has been visiting Carleton University, Ottawa, Ontario, Canada, as a visiting scholar. His current research interests include ICN, caching policies, energy-efficient resource management, and mobility support in ICN.

F. Richard Yu is an associate professor at Carleton University. He received the IEEE Outstanding Leadership Award in 2013, Carleton Research Achievement Award in 2012, Ontario Early Researcher Award (formerly Premier's Research Excellence Award) in 2011, Excellent Contribution Award at IEEE/IFIP TrustCom 2010, Leadership Opportunity Fund Award from Canada Foundation of Innovation in 2009, and Best Paper Awards at IEEE ICC '14, IEEE GLOBECOM '12, IEEE/IFIP TrustCom '09, and the International Conference on Networking '05. His research interests include cross-layer design, security, green IT, and QoS provisioning in wireless networks. He serves on the Editorial Boards of several journals, including *IEEE Transactions on Vehicular Technology* and *IEEE Communications Surveys and Tutorials*. He has served on the Technical Program Committees (TPCs) of numerous conferences, as TPC Co-Chair of IEEE GLOBECOM '14, IEEE INFOCOM-MCC '14, GLOBECOM '13, GreenCom '13, CCNC '13, INFOCOM-CCSES '12, ICC-GCN '12, VTC-Spring '12, GLOBECOM '11, INFOCOM-GCN '11, INFOCOM-CWCN '10, IEEE IWCMC '09, VTC-Fall '08, and WiN-ITS '07; and as Publication Chair of ICST QShine '10 and Co-Chair of ICUMT-CWCN '09.

Tao Huang received his B.S degree in communication engineering from Nankai University, Tianjin, China, in 2002, and M.S. and Ph.D. degrees in communication and information system from BUPT in 2004 and 2007, respectively. He is currently an associate professor at BUPT. His current research interests include network architecture, routing and forwarding, and network virtualization.

Jiang Liu received his B.S degree in electronics engineering from Beijing Institute of Technology in 2005, his M.S. degree in communication and information systems from Zhengzhou University, China, in 2009, and his Ph.D. degree in communication and information systems from BUPT in 2012. He is currently a lecturer at BUPT. His current research interests include network virtualization and future network architecture.

Yunjie Liu received his B.S degree in technical physics from Peking University, Beijing, China, in 1968. He is currently an academician of the China Academy of Engineering, chief of the science and technology committee of China Unicom, and dean of the School of Information and Communication Engineering, BUPT. His current research interests include next generation networks, network architecture, and management.