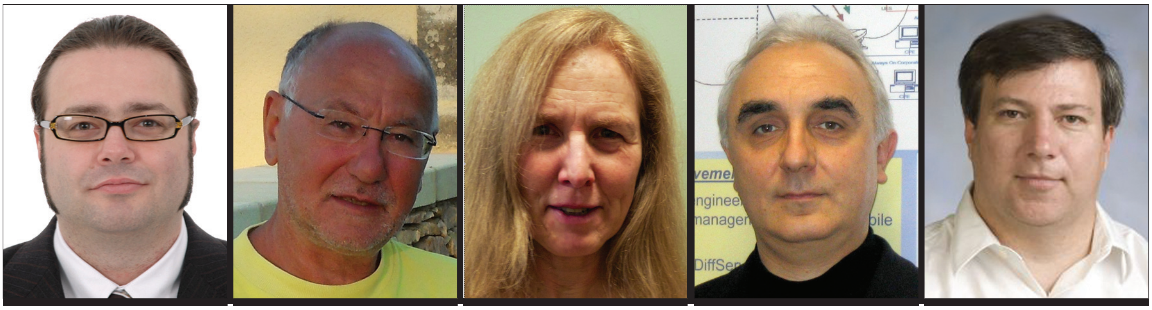
INFORMATION-CENTRIC NETWORKING



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Information-centric networking (ICN) is a relatively new research area that is motivated by significant changes witnessed in the industry regarding applications and services, as well as customer practice and expectations. Indeed, the vast majority of network traffic today (both Internet and intranet) consists of content dissemination, information that is addressed to more than one recipient. This includes not only content created explicitly for public dissemination (e.g., by large organizations such as news agencies, movie studios, and meteorological offices), but also content dissemination between restricted groups of recipients and, increasingly, content generated by end users.

In contrast to a direct email, SMS, or phone call to a relative or friend, a social network post is de facto addressed to a wide(r) audience. This is also the case when a user adds a picture to her public online collection, even when she only has one friend (or "follower") at the moment. Should our user add new friends to her social network profile at a later time, her collection automatically becomes available to others. The user does not need to repost the picture to new friends (i.e., repeat the information delivery process). Thus, to the average user, the Internet is a distributed system for reading information from and writing information to, accessible from many different devices, aimed to bridge the gaps in space and time economically in a way that traditional synchronous telecommunication systems simply cannot. However, the underlying Internet protocols were not conceived and designed for such usage patterns.

The TCP/IP paradigm is not suitable for one-to-many communications despite continuous improvements over the years. It is easier to send a document across the globe to a friend than to share that same document with a group of people sitting in the same room using only local network resources. The original network protocol work on what became TCP/IP was addressing a trustworthy universe of fixed hosts that offered remote access to shared resources to trustworthy individuals and their programs over a dedicated (and for that time significantly overprovisioned) network. As the network expanded, these assumptions started to drop one after the other, calling for patches, add-ons, middleboxes, overlays, and so on. In short, the original set of network invariants is no longer valid for today's Internet.

Along with these changes, the focus has shifted from a location-based system to an information-based one. The IP model is designed to establish a connection between two addresses; in most cases, the consumer simply wants to access the desired content. The exact server that holds the data is largely irrelevant, and the same data may be present on multiple servers, as well as cached at various locations throughout the network. The consumer may want to fetch data from the best available source, simultaneously using multiple sources to fetch the data during the conversation. Although this is feasible today, it requires a good deal of complexity added to the basic model designed to facilitate communication between a source and destination address.

Since the emergence of the World Wide Web, the shortcomings of a network paradigm intended for remote access and shoehorned for content dissemination emerged rapidly, and have been addressed through a patchwork of solutions. In our example of a photo uploaded to a profile, in practice the user's picture is no longer stored in a single host, but is replicated several times over for accessibility, performance, reliability, resilience, and, well, sharing with others.

Building on top of TCP/IP to create solutions for dissemination led to the development of brilliant systems and a trillion-dollar ecosystem spanning the globe. In this process, however, we ended up with systems that make simple things very hard and waste resources such as spectrum and energy. It is remarkable how both the top and bottom of the textbook protocol stack have adjusted over time to evolving usage patterns while retaining TCP/IP. On the top of the stack, application developers addressed performance, security, authentication, authorization, and accounting (AAA), asynchronous operation, distributed caching, and replication, taking specific TCP/IP protocol choices for granted. For example, IP addresses, port numbers, and even timeouts and such are often found intermingling with application logic when they should not.

On the bottom of the protocol stack, while wireless communications took over as a major way of accessing the Internet, they too have been designed with TCP/IP in mind. For instance, within a single broadcast domain, it is typical to establish effectively two unicast channels and employ triangular routing in order to transfer data. In short, the design simplicity of the original TCP/IP protocol stack has been overwhelmed with additions in order to accommodate the evolution of network usage. One can see a certain resemblance of this TCP/IP-centric model with the geocentric astronomical model that once enjoyed wide acceptability. The continuous addition of spheres in the geocentric model in order to keep it aligned with new findings effectively led to the creation of a new model that could explain things better and more simply. With information-centric networking, we may be at a similar point in the way we design, build, and operate networks.

INFORMATION-CENTRIC NETWORKING

Information-centric networking (ICN) enables new ideas for naming and addressing, privacy, security, and trust, as well as business models. ICN builds on current knowledge (and the shortcomings of established practices) regarding network deployment, operation, and management, and borrows elements from earlier research in transport and network protocols, distributed systems, application-layer caching, multicast, and peer-to-peer systems. In contrast to the original IP model, ICN assumes that users, programs, and hosts are in general untrustworthy and mobile, communication is often multiaccess, and primarily interested in retrieving, processing, and sharing information bits, instead of sharing processing and storage resources with others.

This new set of assumptions begs for a revisit of the architecture and protocol concepts for increased efficiency and quality of experience. ICN marks a fundamental shift in communications and networking. ICN focuses on finding and transmitting information to end users instead of connecting end hosts that exchange information. The key concepts are expected to have a huge impact on the familiar textbook protocol stack, in network architecture in general, and will create new opportunities for all associated stakeholders, including equipment vendors, network operators, service and content providers, and above all end users. In Van Jacobson's words, ICN represents the third revolution in telecommunication networks as we move from connecting wires (public switched telephone network [PSTN]) to connecting nodes (all-IP networks) to connecting information (ICN).

This feature topic on ICN starts with the article entitled "A Survey of Information-Centric Networking" by B. Ahlgren *et al.* The article can serve as an entry point to the ICN literature as it reviews in detail four prominent ICN proposals: the data-oriented network architecture (DONA), content-centric networking (CCN), the network of information (NetInf), and the publish-subscribe Internet paradigm (PSIRP). In addition to a survey of ICN, the authors seek to define a common taxonomy of ICN architectures. The authors start with a brief overview of the ICN approach listing the main components in ICN designs and argue for the advantages of ICN approaches. They then delve deeper into the particulars of each of the four proposals and qualitatively evaluate them with respect to several criteria as well as the design trade-offs inherent in each proposal.

The second article in this feature topic by V. Jacobson *et al.* introduces "Custodian- Based Information Sharing" (CBIS). The article makes the case for an information sharing system based on CCN primitives and presents a new information routing model. The article motivates the need for CBIS, and details its design and relationship to CCN. In effect, the article provides an ICN solution for a use case that has become increasingly common: content sharing between friends and family. Through this use case the authors explain how routing works in CBIS and evaluate it using testbed measurements. The authors argue that although similar services are available today, they require significant investments to build and operate. The proposed solution, instead, does not require fixed infrastructure, and can prove as efficient as current solutions.

B. Mathieu *et al.*, also explore the use of ICN for running online social networks in their article "Information-Centric Networking: A Natural Design for Social Network Applications." The article introduces ICN in light of an application similar to Twitter and employing CCN. The authors motivate their work through recent measurement data from operator networks, and explain the impact of the proliferation of online social media today and in the near future on network infrastructure. They provide a short introduction to CCN, explaining how a messaging service like Twitter might run on it. The article includes a comparative, and illustrative, we may add, presentation with respect to network operation when the service runs solely on IP vs. IP and the introduction of content distribution network (CDN) nodes vs. on CCN. The article closes with an evaluation based on simulation runs that points to the performance benefits for both end users and network operators of the ICN approach.

The last two articles in this feature topic concern recent work from the PSIRP and PURSUIT EU-funded projects. G. Xylomenos *et al.* present "Caching and Mobility Support in a Publish-Subscribe Internet Architecture." The article provides an overview of PSIRP, a "clean slate" approach to the future Internet. After introducing the naming scheme and network primitives, the authors explain the separation of functions and proceed with the details of the network design. Emphasis is on illustrating the operation of the three main functions in the architecture: rendezvous, topology management, and forwarding. With these foundational blocks in place, the authors turn their attention to caching and handling mobility in this new network design. As they point out, although many aspects have been fixed, much work is still needed to cover all the loose ends and explore different design trade-offs.

Last, but certainly not least, D. Trossen and G. Parisis present their work on "Designing and Realizing an Information-Centric Internet." The authors present their five design tenets and explain in detail a new protocol stack. This is used in the proposed solution implementation, based on a functional layered model. The article presents a brief overview of how information scoping can work in practice, followed by a description of the exposed service model and application programming interface (API), node implementation using the Click Router framework, as well as further details on dissemination strategies. The authors have made their implementation available to the community; indeed, the article includes results from the first deployment of the code in an international testbed. The article closes with an exploration of how the proposed architecture can be employed to enable other ICN architectures such as CCN, DONA, and IP.

CURRENT RESEARCH TOPICS IN INFORMATION-CENTRIC NETWORKING

Information-centric networking will succeed only if it can provide clearly superior solutions to well-known problems in the current generation of all-IP networks and be introduced to general usage incrementally. In particular, the following topics are critical:

- Naming and addressing: There is currently a strong association between content naming and addressing. Information-centric networking aims to introduce new ways of identifying content in a location-independent manner. What breakthroughs in naming and addressing will make

ICN scalable when faced with a global network of billions of devices and zettabytes of available content? This issue's article by Bengt *et al.* and [1] provide some answers in this area.
- Protocol stack: The original TCP/IP protocol stack was neat and simple. Today's stack is arguably neither, having been extended by patchwork over several decades. Can ICN simplify things? This issue's article by Trossen and Parisis looks into this issue.
- Network architecture: ICN will have a profound effect on network architecture as storage capacity becomes an integral element of all network nodes. What does an ICN network architecture look like? Jacobson *et al.* [2] propose a named content-based architecture.
- Management: Resource/mobility/multihoming management are add-ons to the current architecture. With ICN we have the opportunity to include support for all these aspects right from the start. What are the essential characteristics of a complete management framework that is scalable, flexible, and suitable for ICN? Some of these points are addressed in the article by Xylomenos *et al.* included in this special issue.
- Caching: Information-centric networking is an in-network process that relies on content storage in the network so as to efficiently access popular content, alleviate flash-crowd effects, improve the end-user quality of experience, and increase network efficiency. This raises new issues to be addressed such as buffer management and caching policy [3].
- Energy efficiency: Battery-powered devices abound and will dominate in the future as the primary means of connecting to the Internet. At the same time, there is a strong drive for energy-efficient networking from core networks to access networks, and from data centers to home media centers. ICN has more leverage to make trade-offs between storage/computation/communication [4] — will ICN pave the way to a holistic energy efficient operation?
- Internet of Things (IoT): As the physical world is more and more connected to the digital world through a multitude of sensors and actuators, the current host-centric approach followed in IP networks, typically requiring synchronous, always on, end-to-end connections, stretches beyond its capacity to deliver, introducing further inefficiencies. How does ICN scale in the scenarios envisioned for the IoT, and how does it compare with current IP-based IoT solutions?
- Security and trust is established today end-to-end and through the use of third parties. Synchronous three-way end-to-end connectivity is a prerequisite, and it does not guarantee provenance. Can ICN foster the development of a more secure and trusted global communications infrastructure?
- Business models in the Internet are established between providers according to peering agreements. The new ICN paradigm based on in-network caching may impact the current relationships between players. Which business models could foster a fair relationship between content producers, content providers, and service/network providers?

MORE ABOUT ICN

There are currently several projects that are actively working on ICN topics. Several key projects in the United States (CCN/NDN [2], and previously DONA [5]) and Europe (4WARD [1]/SAIL [6], PSIRP/PURSUIT [7, 8], COMET [9], and CONNECT [10], which adopts the CCN model) have been working on redesigning core network primitives to enable an information-centric network architecture. It is important to note that ICN has generated significant interest in both academia and industry. In fact, key projects in the area of ICN are led by major industrial laboratories around the globe, with most of the activity concentrating in the United States and European Union.

Some of these projects have made open source code available to promote their ICN approach and enable interested researchers to start exploring new ways to solve communication problems and experiment with ICN ideas. These include the following:
- CCNx (www.ccnx.org) aims to develop, promote, and evaluate content-centric networking. It is sponsored by the Palo Alto Research Center (PARC) and is based on the PARC CCN architecture, which is the focus of a major long-term research and development program. The project has created and published open protocol specifications and an open source software reference implementation of those protocols. CCNx can be deployed through middleware software communicating in an overlay over existing networks.
- NetInf code (www.netinf.org) has also been released as open source for the benefit of the wider community. The code base includes extensions to popular applications such as Mozilla Firefox, which allows users to browse NetInf-enabled web sites, and Mozilla Thunderbird.
- PURSUIT takes a publish/subscribe approach for the future ICN network architecture. Researchers at the University of Cambridge developed an open source implementation of an information-centric networking environment called Blackadder. It is based on the Click Router Linux-based platform and implements four different content dissemination strategies within the PURSUIT functional model. Both user- and kernel-space implementations are available (www.fp7-pursuit.eu/PursuitWeb/?page_id=12).

To summarize, information-centric networking is a relatively new research area in communications networks, emerging out of the evolution in the use of telecommunication networks in general and global IP-based networks in particular. It is still a nascent area. Nevertheless, several research groups are currently laying the foundations for what may become the commonplace networking paradigm within a decade. Several approaches have been proposed in the literature so far, each with its own advantages (and drawbacks). All of them claim to perform better than IP for current and evolving everyday use of the network. This feature topic in *IEEE Communications Magazine* aims to introduce ICN to a wider audience, by reviewing salient work done so far, illustrating the area's potential, and pointing to the significant list of topics for further research. Our call for papers attracted authors from 19 different countries, resulting in 40+ paper submissions. Due to the variety of issues addressed in this context, a second feature topic on ICN is already scheduled for the December issue. We would like to thank all authors and expert reviewers who helped us introduce this timely concept. We also thank Steve Gorshe, the *IEEE Communications Magazine* Editor-in-Chief, for his warm support for this special issue. We hope that this feature topic will act as a catalyst, stimulating further research and exploration of commercial applications in this exciting new area.

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BIOGRAPHIES

KOSTAS PENTIKOUSIS (k.pentikousis@huawei.com) is a senior research engineer with Huawei Technologies, Berlin, Germany. From 2005 to 2009 he was a senior research scientist with VTT Technical Research Centre of Finland. He earned his Bachelor's degree in informatics (1996) from Aristotle University of Thessaloniki, Greece, and his Master's (2000) and doctoral degrees (2004) in computer science from the State University of New York at Stony Brook. His research interests include network architecture and protocol design, energy-efficient networking, and information-centric networking.

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