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Information-centric networking: The evolution from circuits to packets to content

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ABSTRACT

Today's information-centric networks (ICNs) represent a 100-year evolution of communication networks from circuit-switched networks to packet-switched networks to ICNs, sharing common features with both of these earlier network architectures, but having many unique characteristics of its own. We describe and survey ongoing research and identify challenges in the modeling, design and analysis of information-centric networks and protocols. We discuss performance modeling frameworks and challenges for ICNs, with a particular focus on content flowing through a network of caches, drawing analogies and distinctions from past research in both circuit-switched and packet-switched networks. We also survey the challenges and recent research results associated with finding content in a network of caches and managing the content in those caches. The challenges posed by mobility (of both the end users accessing content as well as content itself) are also discussed.

1. Introduction

Roughly one hundred years ago, Erlang created the mathematical foundations for analyzing the new telecommunication network of his day – the circuit-switched telephone network, providing the Poisson model for telephone call arrivals [22] and the celebrated Erlang formula for estimating the call blocking probability at a telephone network switch [21]. Fifty years later, Len Kleinrock's seminal Ph.D. thesis [48] used queueing theory to analyze and help make the case for a radically new type of telecommunication network – the packet-switched network, introducing the notions of demand-access resource sharing, statistical multiplexing gains, and underlying modeling assumptions (e.g., the Independence Assumption) [49,50] that would provide the technical foundation for performance models of these networks and their protocols for decades to come.

Fifty years later again, the networking field again finds itself at the doorstep of another potentially profound change – the rise of *content-centric or information-centric networks (ICNs).* While packet-switching network architectures have focused on host-to-host communication – "delivering data between computers or between computers and terminals" [9] – today's Internet is arguably more concerned with connecting people with content and information. Such content includes stored video and audio, web content, software, and more. For example, Cisco's Visual Networking Index noted that Internet video traffic was 64% of all global consumer Internet traffic in 2012 and predicts that by 2017, 51% of all Internet traffic will cross content delivery networks [13]. In such a content-centric worldview, *what* a person wants, rather than *where* it is located, is what matters most; content, rather than the server on which content resides, becomes the starting point.

With an increased focus on content and with nearly 50 years of networking research to draw on, engineers and researchers have begun to design, and in some cases build and deploy, a wide range of content-oriented

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networks. At one end of this range are commercially-deployed server-based content distribution networks (CDNs) such as Akamai [63] and proposed federations of CDNs [4] that re-direct a client to a "nearby" copy of content; once the address of a nearby host containing a copy has been determined, however, that content is then retrieved by the client in a traditional host–host manner. At the other end of this range are more radical designs in which network elements route (and typically cache) content objects amongst themselves, as content is forwarded from content publishers to content subscribers [7,8,18,19,25,28,33,38]. Here, content is requested and forwarded on the basis of a name or other content attribute, rather than on the basis of an address, as in traditional host-to-host communication. In these latter approaches, which we will refer to as *information-centric networks (ICNs),* content objects are the units of information processed, forwarded and stored among network elements. Just as calls were central to circuit-switched networks and packets were central to packet-switched networks, content objects are the central units of information in information-centric networks.

In this paper, we describe ongoing research and identify research challenges in the design and analysis of information-centric networks. In contrast to several recent excellent surveys of ICN architecture and protocols [1,78], our focus here will be on challenges related to the operation and performance of ICNs, and the inter-connected network of content caches within an ICN. Focussing on the modeling and performance analysis is perhaps particularly appropriate, given Len Kleinrock's foundational contributions to our understanding of the modeling and performance analysis of packet-switched networks and their protocols. But a focus on ICN cache networks and their protocols and operation is also appropriate. Like Erlang before him (who was an applied mathematician as well as an engineer, known to crawl into manholes in the streets of Copenhagen to make measurements in the local telephone network), Kleinrock is also known as a modeler, protocol designer (of routing, flow and congestion control, packet voice, and numerous wireless and mobile network protocols) and an experimenter (see, e.g., his account of the first ARPAnet remote login from UCLA to SRI [50]). In taking the long view of the history of circuit-switched, packet-switched, and now information-centric networks, it is fitting to acknowledge an individual whose contributions to packet-switched networks have been foundational, but who has also made important contributions to circuit-switched networks (e.g., research on optically switched LANs [51,58]) as well as information-centric networks (e.g., research on caching and prefetching [41,42]). Kleinrock's pioneering work on packet-switched networks bridges 100 years of networking research – a radical transformation of the circuit-switched networks before, and setting the stage for the information-centric networks of tomorrow.

The remainder of this paper is structured as follows. In Section 2, we discuss the performance modeling framework and challenges in ICNs, with a particular focus on content flowing through a network of caches, drawing analogies and distinctions from past research in both circuit-switched and packet switched networks. In Section 3 we discuss challenges in locating content in a network of caches, and managing the content in those caches. Section 4 concludes this paper.

2. Modeling information-centric networks

2.1. Perspective: circuits, packets, and content

Before delving into the challenges of modeling information-centric networks, it will be instructive to retrospectively consider ICN in the context of earlier circuit- and packet-switched networks. Fig. 1 shows a simple 7-node network with a similar topology in a circuit, packet and ICN setting.

2.1.1. Circuit switching

In the circuit-switched network shown in Fig. 1(a), calls are the basic unit of work. In the simplest scenario, an arriving call must be allocated a free circuit on each link from source to destination in order for the call to be connected. In the example, three calls are connected (two from A to G, and one from B to F), with each call holding one circuit on each link along the path from source to destination. A call that is unable to receive the full set of source-to-destination circuits is *blocked* and receives no resources. In Fig. 1(a), since all three circuits are occupied on the DE link, a new incoming call routed over the DE link (say from A to F) would be blocked. In this case, dynamic alternate routing [29,31] might be used to route this otherwise-blocked call along the path ADCEF. A successfully-connected call holds its circuits for the call's duration and then simultaneously releases these resources when the call terminates.

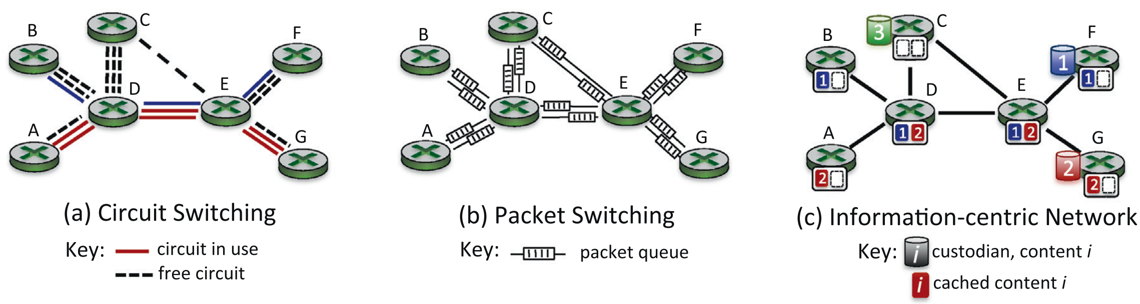

Fig. 1. Circuits, packets and content.