Content Delivery Networks: State of the Art, Trends, and Future Roadmap

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Recently, Content Delivery Networks (CDN) have become more and more popular. The technology itself is ahead of academic research in this area. Several dimensions of the technology have not been adequately investigated by academia. These dimensions include outline management, security, and standardization. Discovering and highlighting aspects of this technology that may have or have not been covered by academic research is the first step toward helping academia bridge the gap with industry or even go one step further to lead industry in the right direction. This suggests a comprehensive survey on research works in this regard. The literature in this area has already come up with some surveys and taxonomies, but some of them are outdated or do not cover every aspect of CDN while others fail to detect existing trends or to develop a holistic roadmap for research on the technology. Furthermore, none of the existing surveys aim at enlightening the dark aspects of the technology that have not been subject to academic research. In this survey, we first extract the lifecycle of a CDN as suggested by the existing research. Then, we investigate previous relevant works on each phase of the lifecycle to clarify where the research is currently located and headed. We show how CDN technology tends to converge with emerging paradigms such as cloud computing, edge computing, and machine learning, which are more mature in terms of academic research. This helps us determine the right direction for further research by revealing the deficiencies in existing works.

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CCS Concepts: • **Networks** → **Network services**; • **Applied computing** → *IT architectures*;

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1 INTRODUCTION AND BASIC CONCEPTS

The increasing number of Internet users and their growing demand for low-latency content delivery has led to the emergence of Content Delivery Networks (CDN). The idea behind CDN is to place the actual responding server as close as possible to the user. This idea is realized using a hierarchy of surrogate servers and cache servers provided by the content provider in which the last level is usually located at the edge of the user network. Figure 1 shows a generalized architecture for a CDN. A legend in the down right corner of Figure 1 shows the symbol by which we represent this architecture for further reference.

In the CDN shown in Figure 1, a hierarchy of servers contribute to the delivery of content. The content servers are mirrored by several interconnected surrogate servers distributed around the Internet. Frequently accessed content items in each local network are cached from the nearest surrogate server into the local edge nodes to improve the access time and quality of service. Different surrogate servers and edge caches can be installed and run by different parties.

When a request for content is issued by a user, the request is routed to the closest cache and the cache is responsible for providing the content. If the content does not reside in cache storage, then an attempt will be made at fetching it from other caches in the same hierarchy level. If a miss occurs again, then the query will be forwarded to the higher hierarchy level where the same procedure is followed. The content caching provided by the CDN reduces the traffic both in the Internet and in the local operator network. Figure 2 shows how the traffic is reduced via the change in the information flow.

There are a variety of techniques that take different approaches to reducing the traffic passing through the Internet. For example, compression [187] and predictive coding [46] try to reduce the traffic caused by each transmission of content. As another example, the principal idea behind coded caching is serving different demands issued by different clients via single content transmission [23]. But as shown in Figure 2, CDN tries to reduce the traffic by reducing the number of transmissions of a single content. In the absence of CDN, different requests for a single content item are served by different copies of the item. These replica are transmitted via the Internet and unnecessarily engage the bandwidth of the links as well as the resources of the intermediate nodes. But in the presence of CDN, a single copy can move through the network to respond to several requests. This reduces the traffic in the Internet backbone and the intermediate nodes.

The application of CDN is not confined to static content delivery. They are used in dynamic content delivery (which requires mutual interaction with the user) and e-commerce transactions as well. They are not used only in Business-to-Business (B2B) interactions between the content owners and content providers. They are finding their applications in Business-to-Consumer (B2C) business models as access providers [35, 167] and telecommunications operators [82, 161] are more prevalently adopting this technology. Moreover, content providers tend to make use of client resources in the context of Consumer-to-Business (C2B) interactions. Furthermore, they can provide

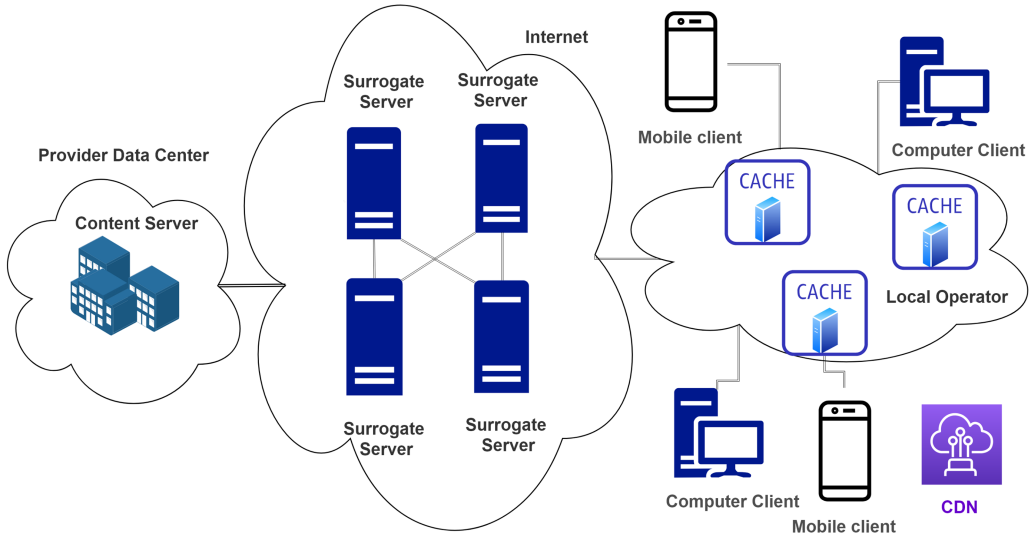

Fig. 1. A typical architecture for current CDN.

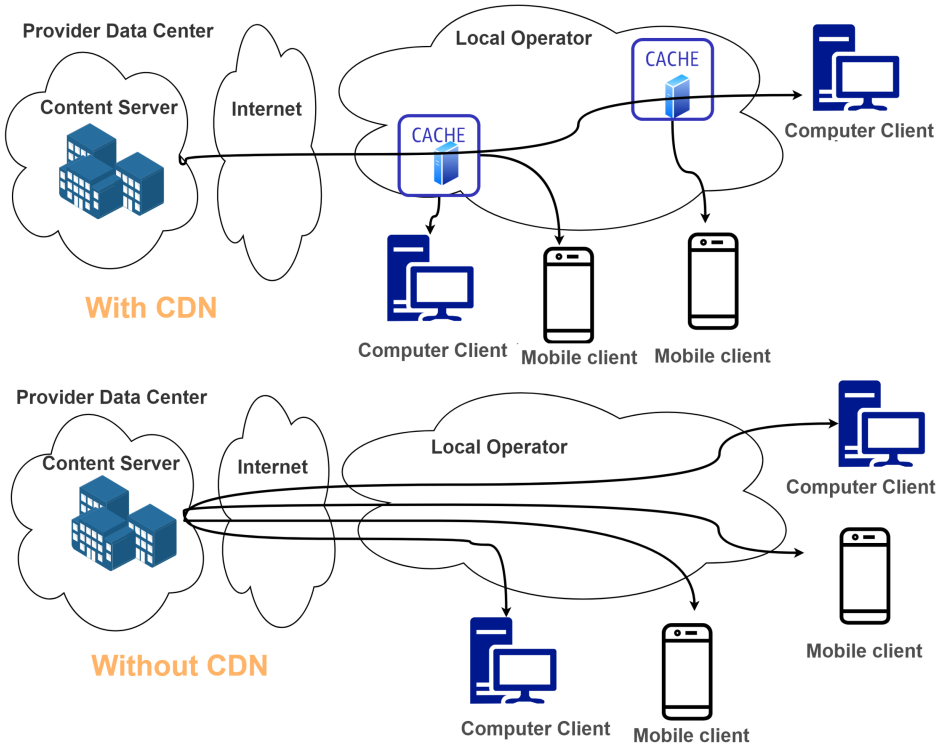

Fig. 2. Information flow with and without CDN.

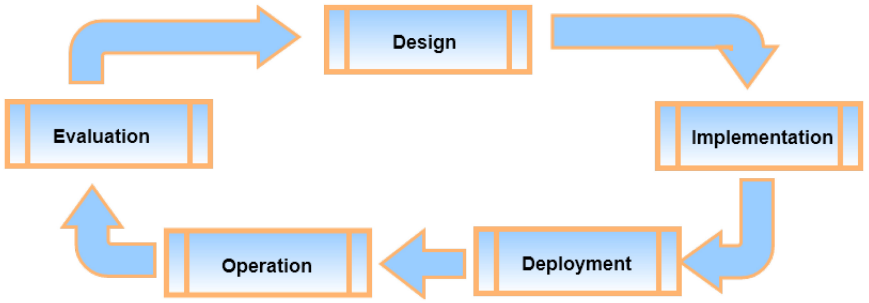

Fig. 3. The current lifecycle of a CDN.

some by-products. For example, since CDN have access to contents used by a spectrum of users, they can be used for collecting valuable behavioral information regarding users.

The CDN market is predicted to grow over 30 billion USD by 2022 [2]. The demand of such a huge market has pressurized the industry into implementing and deploying numerous CDN in different scales around the world. For example, Akamai CDN is handling 20% to 30% of the entire Web traffic [1]. As another example, Amazon Cloudfront is maintaining over 100 edge locations all around the world. One can mention smaller CDN as well such as BelugaCDN with 28 points of presents worldwide. Moreover, a spectrum of services such as vehicle monitoring [173], drone and Unmanned Aerial Vehicle (UAV) monitoring [12, 107], smart health [33], smart cities [32], and e-learning [109] are being provided over CDN. But, the advances in this are not sufficiently supported by academic research in several aspects due to the lack of adequate time. Although there has been some effort toward building prototype CDN in academia [61, 72, 97, 98], still various facets of the technology need to be investigated to make it mature. This creates a need for a survey on CDN related research reports that distinguishes covered and uncovered dimensions and makes it possible to decide further research outlines. In this article, we try to fulfill this need that cannot be fulfilled by a survey on CDN like the existing ones. To the best of our knowledge, there is no recent similar survey in this area.

Putting the state-of-the-art research topics in the area of CDN in a chronological order and comparing the result to typical Information Technology (IT) product lifecycles, we will reach at a seminal lifecycle for CDN as shown in Figure 3. We adopt the lifecycle in Figure 3 as the existing lifecycle for CDN. Detailed investigation of current research topics related to CDN highlights some missing phases and sub-cycles in the overall lifecycle as well as the missing research topics in each individual phase. This enlightens part of the roadmap for future research in this area. The next thing that helps us further develop the future research roadmap by shedding light on the future of the technology is the impact of emerging paradigms such as edge computing and machine learning.

A study on existing and emerging research trends of CDN facilitates a comparison between where the research is currently headed and where it should really be headed. We outline the research trends that are expected to receive more focus down the road. We distinguish between existing and emerging trends. Existing trends are those that have already been remarkably investigated. Emerging trends might not have been subject to a lot of research in the past, but there are logical reasons to anticipate them to turn to trends in the near future.

The following features make this survey different from previous surveys or reviews related to CDN.

- In this article, we do not present a classification or taxonomy of CDN. Instead, we classify the reported research works regarding CDN.
- We do not present case studies.

- The lifecycle and the trends presented in this article are not inspired by best practices or industrial de factos. Rather, they are big pictures made by putting research titles together.
- We do not concentrate on the business-related aspects such as provider or commercial products.

The rest of this article is organized as follows. Section 2 mentions previously published surveys, taxonomies, and similar works related to CDN and highlights their shortcomings to clarify our motivations to this survey. Section 3 studies the state of the art. Section 4 discusses the existing and emerging trends. Section 5 examines the deficiencies in the state of the art as well as current trends to outline the proper direction for further research in this area. Section 6 concludes the article and suggests topics for continuing our work.

2 THE NECESSITY OF A SURVEY ON RESEARCH IN CDN

Reviewing CDN and related topics has already been considered by several researchers. In this section, we study previous surveys and highlight the missing points in them that are covered by this survey.

2.1 Existing Surveys and Their Orientations

The dynamic data delivery over CDN was considered in Reference [148] where the authors identified and classified some challenges in this area and also provided a categorization of existing streaming CDN.

In References [39] a survey was made only on CDN providers. A very seminal classification of CDN was presented in this research. Another brief seminal survey on the approaches to implementing CDN was presented in Reference [41].

The authors of Reference [127] focused on replica server placement algorithms in CDN. They mentioned cost minimization and Quality of Service (QoS) assurance as the main objectives of replica server placement and argued that these objectives are becoming more complex and more significant with the emergence of new paradigms such as cloud. They outlined the requirements of a replica server placement algorithm. Moreover, they categorized existing algorithms and compared them against each other according to the mentioned requirements.

A survey on content placement algorithms in cloud-based CDN was presented in Reference [129], where they also investigated different design issues, practical implications, and related research challenges.

An attempt was made in Reference [9] to characterize the advantages and disadvantages of peer-assisted CDN by presenting a systematic taxonomy of these CDN as well as highlighting the related challenges. The authors in this report tried to predict some future trends in this area.

The authors of Reference [163] focused on open challenges in cloud-based CDN. They mentioned some advantages to cloud-based CDN including pay-as-you-go, increased number of points-of-presence, interoperability, and support for a wider variety of applications. Moreover, they classified the issues and challenges arose by cloud-based CDN and investigated the existing solutions. They examined the architecture and services of cloud-based CDN and studied some existing samples.

The evolution of CDN and the state of the art (at the time of publication) were studied in Reference [114]. The authors studied different technological aspects of CDN. They highlighted existing trends and presented some guidelines for future research in this area.

A taxonomy of CDN was presented in Reference [114] and Reference [115]. In these reports, the authors studied the evolution of CDN and presented a layered CDN architecture suggested by related research. This report classified existing CDN into different classes in terms of four

issues: (1) CDN composition, (2) content distribution and management, (3) request routing, and (4) performance measurement. Moreover, a survey on existing commercial and academic CDN was presented along with a mapping between the taxonomy and the existing CDN. Furthermore, some outlines were suggested for further research.

The authors of Reference [158] argued that fast content delivery is an absolutely critical user demand and referred to CDN as an improved variant of Web caching that fulfills this demand. They divided the operation of a CDN into four phases: (1) caching the contents from the origin content server by surrogate severs, (2) request routing to the surrogate servers, (3) distribution of the requested contents from the origin server to the surrogate servers, and (4) providing accounting information to the origin server via an accounting mechanism. They continued by discussing the trends in each of the mentioned phases (at the time of the research). Furthermore, this research introduced and compared some CDN providers.

In Reference [15], the main research areas in the field of CDN were studied. Among the areas addressed in this research, we can refer to architecture design, caching and replica management and request routing along with related measurement techniques. This is the closest existing survey to our survey in this article, but it has is own deficiencies. For example, it is too outdated, and it does not cover aspects such as the ecosystem and the lifecycle of a CDN. Moreover, it does not highlight current research trends or provide outlines for future research.

2.2 Motivation

Some drawbacks in the mentioned surveys motivate us for this article. We refer to some of these drawbacks in the following.

- After Reference [15] (published in 2003), no survey has focused on research in the area of CDN.
- Some existing surveys are too outdated to be considered as proper references for an increasingly complex technology such as CDN.
- Each of the existing surveys has focused on some aspects, applications, components, or types of CDN. They have not covered the general concept of CDN.
- Some surveys have not presented any guidelines or directions for further research.
- Some works in this area have not studied even existing trends.
- In some surveys, the approach is quite different from our approach in this article. In this article, we classify existing research on the basis of the lifecycle and the architecture of CDN, while other surveys have taken different approaches.

Table 1 briefly compares existing surveys related to CDN. The first and the second columns in Table 1 show the research report and its publication year, respectively. The third column distinguishes between review-type surveys and taxonomies. The fourth column indicates the business, industrial, or academic orientation of the survey. The fifth column shows whether the classifications in the survey are based on lifecycle phases or not. In this column and the next ones, $\mathcal{X}$ and $\mathcal{O}$ represent *YES* and *NO*, respectively. The sixth column shows whether the corresponding report focuses on research in CDN or not. The seventh column contains a $\mathcal{X}$ if the corresponding survey covers the general concept of CDN and a $\mathcal{O}$ otherwise. The eighth and the ninth columns indicate the existence or the lack of current trends and future guidelines, respectively.

3 WHERE WE ARE: STATE OF THE ART

This section consists of five subsections, each of which discusses the previous research in one of the CDN lifecycle phases introduced in Figure 3.

Table 1. The Summary of Existing Surveys

Report	Year	Tax./Rev.	Orientation	Lif. Cyc.	Res.	Covered Topics		
						Gen. Conc.	Curr. Trends	Fut. Guide
[148]	2018	Tax. Rev.	Indust./Acad.	O	O	O	O	O
[41]	2017	Rev.	Acad.	O	O	X	O	O
[127]	2017	Tax.	Acad.	O	O	O	O	O
[129]	2017	Rev.	Acad.	O	O	O	O	O
[9]	2017	Rev.	Indust.	O	O	O	O	X
[39]	2015	Rev.	Bus.	O	O	X	O	O
[163]	2015	Rev.	Indust./Acad.	O	O	O	X	O
[116]	2008	Rev.	Acad.	O	O	X	X	X
[115]	2008	Tax.	Acad.	O	O	X	X	O
[114]	2007	Tax. Rev.	Indust./Acad.	O	O	X	O	X
[158]	2003	Rev.	Bus.	O	O	X	X	X
[15]	2003	Tax.	Bus.	O	X	X	O	O

3.1 Design

In this article, design is considered as the first phase in a CDN's lifecycle. Among the design-related topics covered by academic research, one can refer to the following.

- Study of Design Considerations
- System Model Design
- Ecosystem Study and Development

3.1.1 Study of Design Considerations. The research works in this category can be further classified under three separate topics as explained below.

Design Issues, Challenges, and Principles. To the best of our knowledge, there is no comprehensive research aiming at the identification of general CDN design principles, challenges, and issues. However, there are some reports focusing on some special cases. The authors in Reference [139] mentioned some features specific to CDN owned by mobile phone operators. In their discussion, these features suggest some specific design principles for this kind of content delivery networks. Issues and challenges faced while augmenting a CDN to support some extra content-related operations such as content generation and modification were addressed in Reference [118].

Design Objectives and Parameters. The previous studies highlight two major topics of interest regarding CDN design parameters: improving parameters and examining the tradeoffs between parameters. When it comes to improvement, one can highlight five major design parameters and objectives addressed in the literature: performance, cost, scalability, security, and fault-tolerance. But the only studied tradeoff is the classical tradeoff between cost and performance.

- **Improving Design Parameters:** The studies that focused on each of the mentioned design parameters are reviewed in the following.
  - **Performance:** There are some research reports that study the performance gain of CDN compared with traditional media distribution over the Internet [91]. However, coding has received a significant focus from researchers as a general approach to improving performance in different types of CDN [184] and different services [185]. Moreover, there are some specific coding-based performance improvement techniques to which we can refer.

For example, multiple-description coding was studied in Reference [10] as an approach to improve the performance of video streaming in CDN.

- **Cost:** The authors of Reference [128] argued that most researchers in the field of CDN focus on content delivery latency and traffic as major measures for cost as they look at cost from the user's point of view. They emphasized bandwidth and storage as owner-side cost measures. They presented an approach to exploiting generic optimization algorithms to reduce storage costs.
- **Scalability:** Scalability can be considered as a better studied design objective compared to performance and cost. Researchers have focused on improved load balancing and bandwidth scheduling as well as hierarchical design as efficient techniques to make CDN more scalable. Relevant studies in this area are discussed in the following.
  - **Traffic Load Balancing:** A hierarchical load-aware scheme for content server selection was proposed in Reference [67]. A cost-based distributed load balancing strategy was presented in Reference [134]. Even fuzzy-based methods have been considered for this purpose [124].
  - **Resource Scheduling**: A resource scheduling scheme for a three-tiered 5G-based heterogeneous CDN was studied in Reference [30] that meets the signal-to-noise requirements of 3G networks.
  - **Hierarchical Design:** A hierarchical CDN architecture was considered in Reference [51]. In this architecture, caches are located in both edge and core tiers of the network. The authors in this report deemed currently existing content replication algorithms too complex to be used in practice and especially in hierarchical CDN. They proposed a clustered replication method that is claimed to be less complex and more suitable for a hierarchical architecture.
- **Security:** CDN security is in fact a matter of both network and information security. However, among several items of information and network security, only a few have been partially addressed with regard to CDN so far. One can refer to ownership claiming, intrusion detection, penetration testing, and privacy as some related items studied in this area. Relevant research works are discussed in the following.
  - **Ownership Claiming:** Resource claiming as well as copyright and content claiming have previously been studied as two topics related to ownership claiming.
    - **Copyright and Content Claiming:** In general, watermarking is a prevailing technique for content copyright protection. Watermarking in CDN was studied in the context of `H.264` streamed video in Reference [27].
    - **CDN Resource Claiming:** A fine-grained framework has been introduced in the literature that allows content generators to claim CDN resources [159].
  - **Intrusion Detection:** Simultaneous incorporation of network and information in CDN clearly suggests the existence of comprehensive intrusion detection schemes. But there are hardly more than a few research works available in this regard. A related topic is traffic anomaly detection studied in Reference [45].
  - **Penetration Testing:** Penetration testing is another necessary requirement of network/information security management frameworks. In the context of CDN, some related topics such as packet eavesdropping [60] and censorship evasion have been considered by researchers. Moreover, the authors in Reference [95] demonstrated how an information-centric networked can be exploited to lunch a saboteur content delivery network distributing malicious content and code.
  - **Privacy:** Privacy is another obvious implication of CDN security. Among research reports focusing on this topic, one can refer to Reference [36], which proposes the use

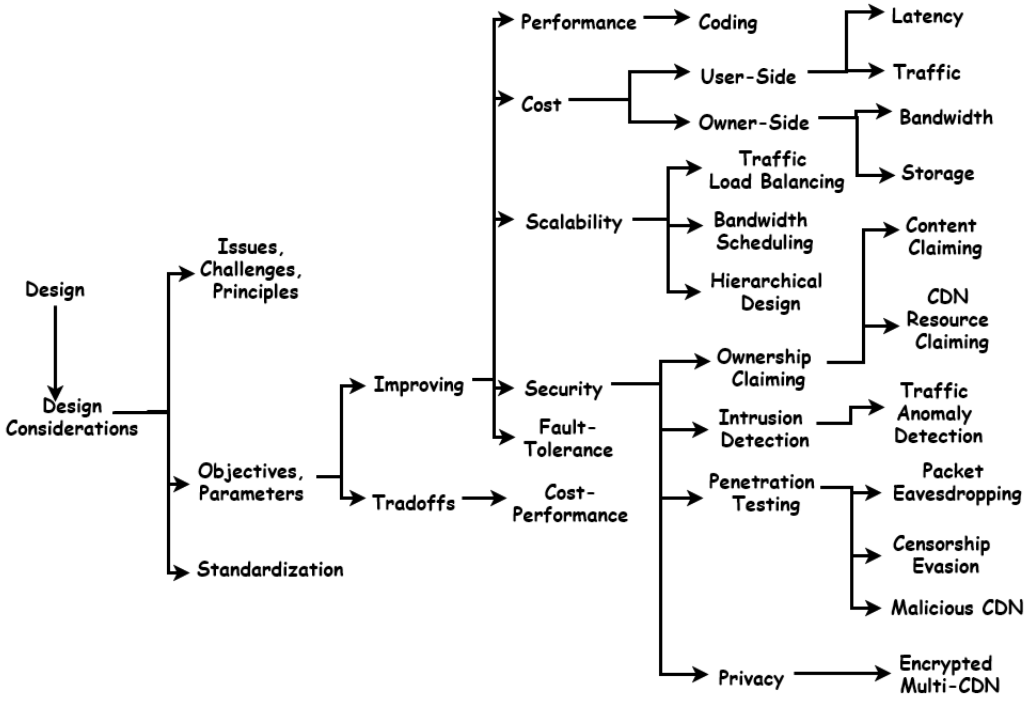

Fig. 4. Research on design considerations.

of previously introduced multi-CDN [157] as an approach to improve privacy. The authors of Reference [36] introduced an encrypted framework to keep curious CDN providers from accessing user-requested contents in plaintext while searching and caching them.

—**Fault-Tolerance:** Fault-tolerance in CDN has not been comprehensively studied by researchers. There are only a few relevant works in this area, among which we can refer to the framework presented in Reference [3]. This framework aims at reducing stall times through controlling affecting parameters such as caching space and bandwidth allocation. Another variant of this framework was presented later in Reference [4].

- **Tradeoffs among Design Objectives and Parameters**
  —**Cost-Performance Tradeoff:** Some research works indirectly highlight the tradeoff between the performance and the cost. For example, a distributed load balancing algorithm for CDN has been presented in Reference [134], which reduces the content migration cost by bounding migration distance but sacrifices the performance in terms of queue balancing. Further, a decision support system has been proposed in Reference [178] for analyzing this kind of tradeoff.

Standardization. It seems that adequate effort has not been made in the standardization of CDN. Among few research works in this regard, we may point out the one reported in Reference [97], which is a feasibility study on standard SIP/RTSP-based CDN.

Figure 4 shows the classification of the works related to the study of design considerations.

3.1.2 System Model Design. The best covered topics related to system model design are as follows:

- Architecture Design
- Components

The research reports related to each of the above topics are discussed below.

Architecture Design: An architecture for distributed CDN was proposed in Reference [102]. The idea behind this architecture is making use of the resources of common Internet users instead of uncommitted volunteer users as in traditional peer-to-peer architectures. One can refer to a few more miscellaneous works such as the aforementioned ones, but adaptation to the trends in network and application architecture design such as multi-tiered architecture and service-oriented architecture is the topic that has received the most academic research in this area. There are a few works in this regard that are studied below.

- **Multi-tier Architecture:** A two-tiered architecture for video streaming in cloud-based CDN has been proposed in Reference [53]. A priority-based variant of round-robin scheduling is performed in the first tier of this architecture. The second tier builds dedicated peer-to-peer networks one for each video. Furthermore, one can refer to the multi-tiered caching analysis presented in Reference [4].
- **Service-oriented Architecture:** In Reference [28] the authors focus on video-on-demand services and propose a service-oriented architecture that makes use of an added layer consisting of home boxes for content delivery.

Components: The components of a CDN that have been studied in existing research works can be categorized into three main categories as explained below.

- **Owner Side:** Among owner-side components of a CDN, servers, applications, and storage have been addressed by academic research. We discuss each topic separately in the following.
  - **Servers:** A variety of issues regarding CDN servers have been examined so far. For example, a bit rate selection strategy for video streams was presented in Reference [181] that takes into consideration not only client and network parameters but also server capacity. As another example, a topology-based clustering method was proposed in Reference [174] to take advantage of server cooperation. Furthermore, we can refer to server selection and content routing as two classical challenges in this regard. For example, a two-level hierarchical content routing strategy was discussed in Reference [106] that performs content routing at inter-cluster as well as intra-cluster levels. Moreover, a server selection scheme was proposed in Reference [108] that depends on information provided by a monitoring server.
  - **Applications and Processes:** Process load balancing can be referred to as a related topic considered by researchers. For example, a fuzzy-based load balancing scheme has been presented in Reference [124]. As another related topic studied in previous research works, we can mention request routing. A request routing method for cloud-based CDN has been proposed in Reference [44]. Another request routing scheme—again for CDN over cloud—has been presented in Reference [59].
  - **Storage:** The only bold storage-related topic that can be traced through existing research reports is de-duplication. A method for building a CDN over an information-centric network has been introduced in Reference [153] that keeps contents from being duplicated among surrogate servers by affiliating each content to a specific server.
- **User Side:** Clients are important user-side components that are receiving more and more focus by researchers [28]. In this regard, one can even refer to an attempt at the design of a client-centric CDN reported in Reference [155].

- **Third Party:** The underlying infrastructure can be provided by a third party. These items have been of interest to researchers, and we will discuss them separately.
  - **Network:** The network is the first infrastructure component that has been highlighted by previous research. Different layers of the network should support high-performance content delivery, and this has been reflected in existing research works.
    * **Physical and Data Link Layers:** Adaptation to the existing standards and protocols is a challenge identified by researchers. For example, the requirements of building a CDN over a wireless network have been studied in Reference [142].
    * **Network Layer:** Routing is probably the most important challenge for supporting CDN in the network layer. There have been some attempts at modifying the traditional IP routing to give a better support to content delivery [93]. Integration of heterogeneous networks is another concern in this regard [30].
    * **Transport Layer:** Supporting CDN in the transport layer has been a concern in research [70]. One can mention traffic management, congestion management, and QoS among transport layer technical challenges considered by researchers. These challenges are discussed in the following.
      . **Traffic Management:** There are some research works that focus on adding traffic patterns to the considerations of the caching system [150].
      . **Congestion Management:** Research reported in Reference [85] studied CDN on top of mobile networks were base stations provide storage for the purpose of content replication. Blind request redirection was considered as a source of traffic congestion in this report. A multi-objective content placement and request redirect optimization problem was examined in this research to address the congestion problem.
      . **Quality of Service:** A QoS management scheme was proposed in Reference [74] that works according to three main parameters: delay, packet lost rate, and server load. Moreover, there are some studies that focuse on the design of QoS-aware caching systems [62].
    * **Application Layer:** In the application layer, researchers have focused on two main topics that are addressed below.
      . **Video Transcoding:** Video transcoding has been considered as a technique to help integrate networks that are heterogeneous in lower layers [183]. Video transcoding has been considered in cloud-based CDN as well. The authors in Reference [29] proposed an approach to transcoding videos according to a popularity ranking derived from recorded logs.
      . **Quality of Experience:** The authors in Reference [24] designed a framework for detecting anomalies related to Quality of Experience (QoE) in distributed content delivery applications. They demonstrated how the common dynamic server selection strategies such as the one used by Google can have an adverse impact on end user's QoE in prevailing video streaming applications such as YouTube. Another study focused on the unfairness of existing QoE management mechanisms in mobile-based CDN [179]. This research proposed some extra nodes referred to as mobile CDN service points to be deployed in mobile CDN and demonstrated their QoE-related benefits in terms of fairness.
  - **Caching System:** The caching system is the second infrastructure component that can be traced trough current research. Research works in this area can be divided into two main categories. The first category includes designing a whole caching system or part of it, and the second consists of works examining the impact of different parameters on the caching system. Each category is explained below.

* **Design:** Design-related works again fall into one of the following categories.
  . **Entire Caching Mechanism:** The first category of research works in this area covers an entire caching mechanism.
  Cache Architecture Design: In this branch, we can refer to the cache architecture proposed in Reference [71]. This architecture consists of two layers, one with a small memory size working as the edge and the other equipped with a large database working as the parent. A monitoring agent in the edge cache prepares logs and sends them to the parent cache to be stored in a big data platform. The knowledge discovered from the big data is used while deciding caching policies.
  Caching Scheme Design: The use of cooperative caching has been proposed as a solution for high-performance on-demand content delivery [105]. Moreover, caching in telecommunication company (telco) has been studied in Reference [161].
  . **A Single Phase:** The second category of studies on the design of caching system focuses on only one caching phase.
  Pre-Caching: The authors in Reference [77] proposed a pre-caching mechanism for CDN in which related contents are pre-fetched into the cache along with the requested content. Their pre-fetching mechanism works in a multi-path manner in the sense that a group of edge servers cooperate via issuing simultaneous requests for contents demanded by each of them.
  Placement: A cache placement strategy for two-tier wireless CDN was proposed in Reference [146] that depends on different channels for content dissemination and content services.
  Replacement: The authors in Reference [145] modeled the content replacement problem in a limited-storage cache as an Markov Decision Process (MDP) and proposed a replacement scheme for maximizing cache hit ratio in wireless CDN.
* **The Impact of Parameters:** Three features were proposed in Reference [172] to characterize an access pattern on the basis of geographical request distribution. The authors defined three different access patterns (among several possible patterns) according to the features and demonstrated how they can affect the efficiency of the caching system in a CDN. Another study took into consideration the temporal request distribution in addition to the spacial (geographical) request distribution [151]. There is another study that focuses specifically on the impact of access patterns on the performance of the caching system in telco CDN and hybrid P2P-CDN [13].

Figure 5 shows the research works related to system model design.

3.1.3 Ecosystem Study and Development. The following topics have been studied regarding ecosystem study and development.

- Adaptation to Traditional Technologies and Emerging Paradigms
- Interaction between CDN and Clients
- Interaction among CDN

Each of the above items is studied in detail in the following.

Adaptation to Traditional Technologies and Emerging Paradigms: Several research works have proposed approaches to hooking CDN to each other, to prevailing networking technologies such as peer-to-peer networks, or to emerging paradigms such as cloud computing. These works are reviewed in the following.

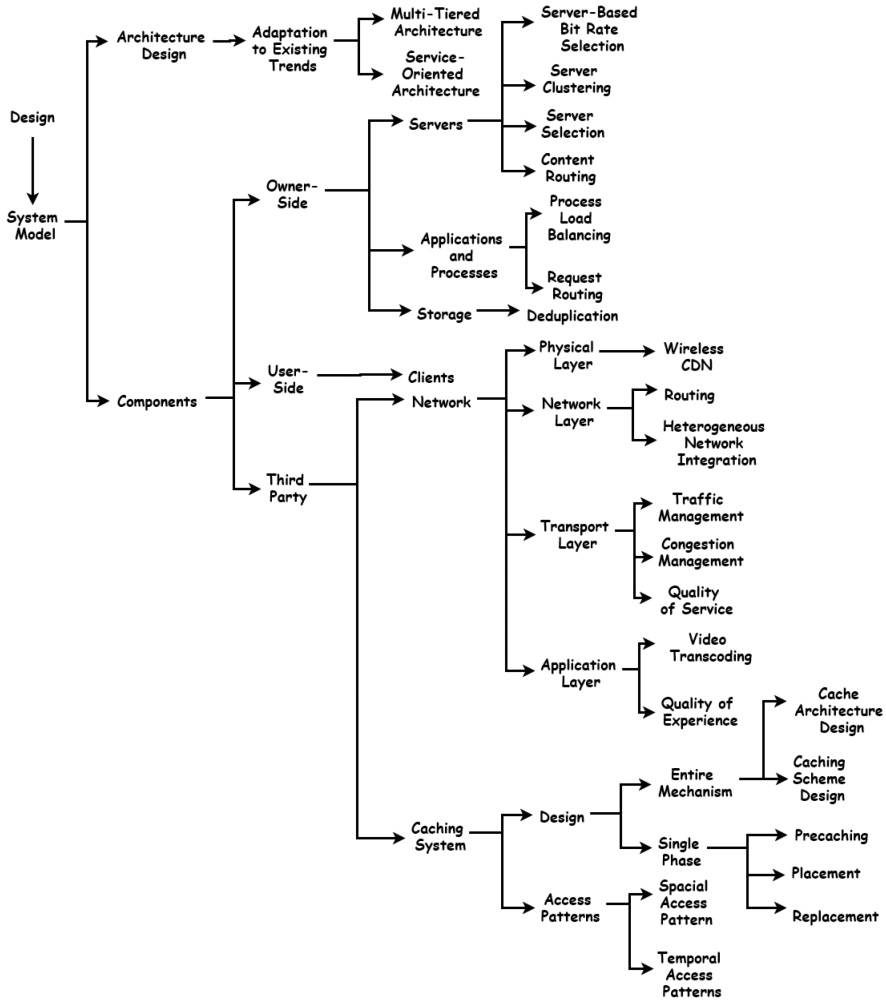

Fig. 5. Research on system model design.

- **Adaptation to Communication Models**
  - —**Peer-to-Peer:** Client-level peer-to-peer (P2P) communication in CDN has been studied in several reports, as it helps clients contribute to the bandwidth allocation. For example, research reported in Reference [170] has proposed a CDN architecture in which clients are peered to groups by the use of a modified variant of the Kamdelia peer-to-peer topology management protocol. A prototype of another P2P-based CDN was presented in Reference [138]. The latter CDN manages the P2P network in a hierarchical structure to avoid the adverse effect of pure P2P and central P2P on the quality of service as well as the reliability. Further, a micro-payment mechanism has been presented in Reference [103] to motivate clients to voluntarily participate in P2P client networks.
  - —**Multicast:** Multicast is another communication model considered by CDN researchers. But the latter communication model is used between the customer network and the used network. A multicast communication framework based on Wavelength Division Multiplexing (WDM) between servers and clients has been proposed in Reference [83].

Multicast in application level coupled with cooperative caching was examined in Reference [105]. Moreover, multicast in CDN over satellite was studied in References [52, 176].

— **Any-cast:** The idea behind any cast in CDN [8, 49] is to forward the user's request to the closest server that eliminates the need for costly DNS support in small CDN.

- Interaction between CDN and Other Technologies
  - — **Internet and Web:** Research reported in Reference [141] has studied the impacts of the increasing complexity of CDN on different aspects of the Internet ecosystem. Further, some strategies have been proposed in Reference [104] that make CDN more profitable for web applications via placing different contents in a single web page on different cache servers depending on their sizes.
  - — **Cloud:** The interaction between the CDN and cloud technology has been examined in numerous recent research works [16, 149]. Among different aspects of this interaction, the following topics have received the most amount of focus:
    - * System Model, Architecture and Prototyping of Cloud-based CDN [34, 53, 98, 110],
    - * Applications and Services on Top of Cloud-based CDN [81],
    - * Caching Performance in Cloud-based CDN [124, 125],
    - * Integration of Heterogeneous Platforms in Cloud-based CDN [29],
    - * Service Delivery in Cloud-based CDN [40],
    - * Storage Management in Cloud-based CDN [128, 165],
    - * CDN as a Service [14, 48, 123].
  - — **Fog Computing:** In addition to cloud computing, fog computing has been considered as another technology that can potentially interact with CDN [7]. This kind of interaction is imminent, because edge nodes play pivotal roles in both technologies.
  - — **Information-Centric Networking:** The possibility of making use of CDN to provide ubiquitous caching for information-centric networks along with the resulting security risks have been studied in some reports [95].
  - — **Telecommunication:** Recently, telecommunications companies (telcos) have tried to take advantage of the popularity of content delivery services and the efficiency of CDN as they can place cache servers closer to the clients than traditional CDN. The CDN implemented on the basis of this philosophy is referred to as telco CDN [82, 161]. Moreover, CDN researchers have considered different kinds of telecommunication technologies as part of the networking infrastructure in CDN. Among these technologies, one can refer to the ones explained in the following.
    - * **Mobile Networks:** Mobile phones have emerged and become increasingly popular in recent decades, and the research in the field of CDN has followed this trend [76, 166]. Among different challenges encountered in deploying CDN on top of mobile networks, researchers have focused on handover awareness [18], congestion avoidance [85], QoE [179], and so on.
    - * **Satellite Links:** Customizing CDN architecture [176] and the service delivery over CDN [88] to unicast and multicast communications over satellite links has been a topic of research in recent years.
  - — **Vehicular Networks:** Some recent research reports argue that the clusters of smart vehicles connected to intelligent networks can serve to content delivery as virtual servers [5]. This possibility has been examined in platforms such as vehicular micro-clouds [156].
  - — **UAV:** The interaction between CDN and UAV technology is quite natural, as they can mutually support each other. UAV can be used for carrying CDN access points to rural area and hard-to-reach regions, while CDN can be used to handle contents such as image

and video transmitted by UAV. This interaction has been studied in Reference [107] and Reference [12].

- **Hybrid CDN:** Some kind of tight interaction with other technologies appears in hybrid CDN namely CDN-P2P and CDN-ISP (Internet Service Providers).
  - **Hybrid CDN-P2P:** In recent years, Hybrid CDN-P2P has been studied as an efficient architecture for media streaming services [182, 186]. Challenges such as flow control [96] and energy efficiency have been examined in this regard [90].
  - **Hybrid CDN-ISPs:** Like the case of telecommunications network operators, ISP can be considered as access points close to Internet users. Thus, it is reasonable to investigate the possibility of establishing connections between CDN and ISP. This possibility has been studied in some research works such as Reference [167] and Reference [35].
- Interaction between CDN and Clients
  After interaction with existing and emerging technologies, CDN need to make a more efficient interaction with their clients to develop their ecosystem and improve their performance and quality of service. This has been considered by researchers and research works in this regard have focused on two main topics as explained below.
  - **Client Peering:** The term *peering* may be used for two concepts in the field of CDN: first, for interaction between peer-clients and, second, for interaction between peer CDN [156].
  - **Collaborative CDN:** In a collaborative CDN, clients form a community to share their contents and storage resources. These clients can be individuals, website owners, and so on. Users welcome this idea, because it allows them to connect to CDN without paying more than the normal costs of Internet connectivity [177]. However, CDN providers can reduce their expenditures by avoiding extra cache servers. Two sample realizations of collaborative CDN have been reported in Reference [117] and Reference [47].
- Interaction among CDN
  The ecosystem of CDN is being developed by recent research. In addition to making CDN adaptable to other technologies, the idea of improving the performance and service delivery via establishing interactions among CDN is well developed. In the following, we discuss some aspects of the latter interaction.
  - **Peering and Peer-assisted CDN:** In addition to the previously discussed work reported in Reference [156], a service-oriented architecture for peering between CDN has been proposed in Reference [21]. Moreover, some suggestions have been presented in Reference [112] to help CDN providers come to a proper Service Level Agreement (SLA) for sharing their services. Further, some economical aspects of CDN peering have been investigated in Reference [113]. The development of the notion of peering-based CDN have led to the emergence of virtual organizations [57, 112]. A virtual organization is a collection of individuals or companies that come together in a joint venture to build a shared CDN.
  - **CDN Brokers:** CDN brokers allow a content provider to get service from multiple CDN. The tradeoffs and challenges induced by the use of CDN brokers have been studied in Reference [101] and Reference [100]. The authors in Reference [100] have attempted to predict the implications of CDN brokers for future CDN.
  - **CDN Internetworking:** A study reported in Reference [111] argued that separate islands of CDN are usually not cost-effective, because they often suffer low resource utilization in non-peak times. This research proposed CDN inter-networking as an effective solution to this problem. Some experimental results from a lab implementation of a CDN interconnect was reported later in Reference [19].

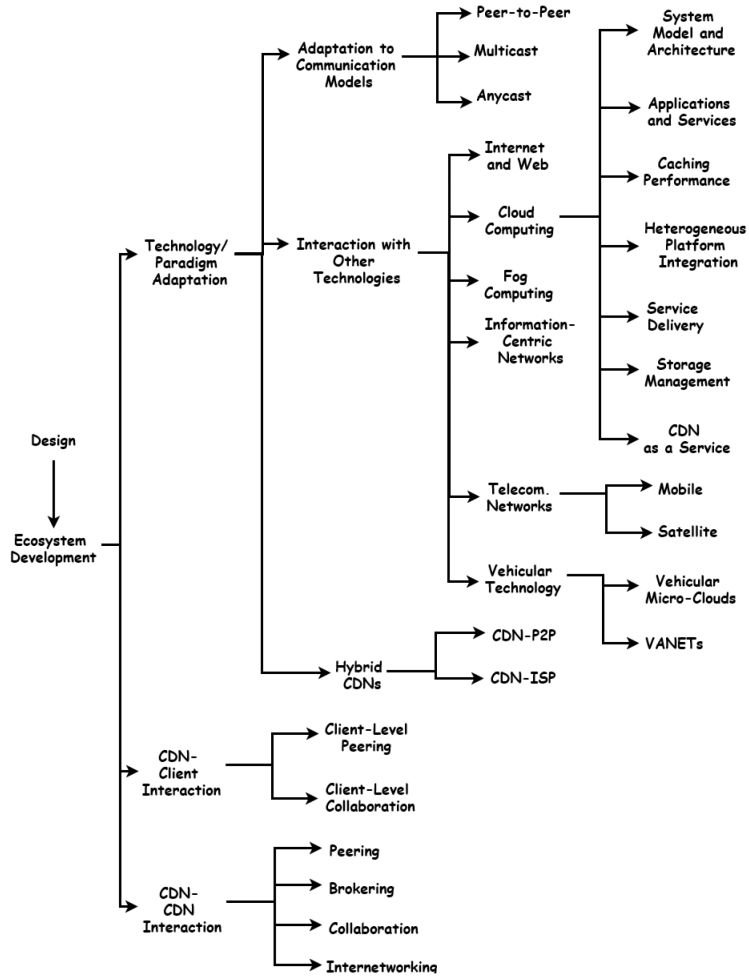

Fig. 6. Research on ecosystem study and development.

Figure 6 shows the works regarding ecosystem design and development.

Table 2 lists the research reports related to the design phase in CDN lifecycle for ease of access. The list is classified in two levels.

Figure 7 shows the ecosystem of a CDN as suggested by existing research works.

3.2 Implementation

Implementation phase CDN have not been well studied until recently [98]. However, there are some reported research that can be categorized as follows:

Virtualization: Virtualization is an overlaying technique based on on-demand resource allocation that aims at improving resource utilization. After successful application in the implementation of virtual servers and software-defined networks, this technique has been considered as a cost-effective implementation approach. For example, a re-configurable virtual CDN platform has been proposed in Reference [168], which allows different content delivery strategies to be dynamically used in response to changes in runtime parameters. Also, some hints for physical resource planning in a virtual CDN have been presented in Reference [92].

Table 2. List of Research Reports Related to the Design Phase

Class	Subclass	List of Reports
Design Consid.	Issues, Challenges and Principles	[118, 139]
	Objectives, Parameters	[3, 4, 10, 27, 30, 36, 36, 45, 51, 60, 67, 91, 95, 124, 128, 134, 134, 157, 159, 178, 184]
	Standardization	[97]
System Model	Architecture Design	[4, 28, 53, 102]
	Components	[13, 24, 28–30, 44, 59, 62, 70, 71, 74, 77, 85, 93, 105, 106, 108, 124, 142, 145, 146, 150, 151, 153, 161, 172, 174, 179, 181, 183]
Ecosys. Devel.	Technology/Paradigm Adaptation	[5, 7, 8, 14, 16, 29, 34, 35, 40, 48, 49, 52, 53, 76, 81–83, 85, 90, 95, 96, 98, 103–105, 110, 123–125, 128, 138, 141, 149, 156, 161, 165–167, 170, 176, 176, 179, 182, 186]
	CDN-Client Interaction	[47, 117, 177]
	CDN-CDN Interaction	[19, 21, 57, 100, 101, 111, 112, 112, 113, 156]

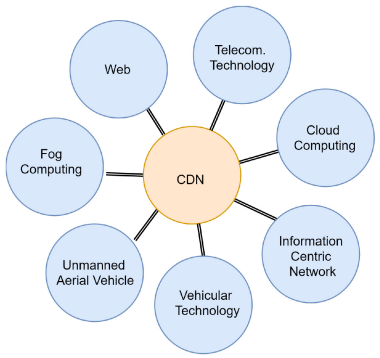

Fig. 7. The CDN ecosystem.

Software Implementation: A software-driven CDN implementation framework has been presented in Reference [42], which allows several small content providers to overlay their CDN on top of a single set of cache servers provided by the infrastructure provider. Moreover, some challenges of software-driven CDN such as server selection have been examined in Reference [154].

Crowdsourcing: The authors in Reference [144] argued that crowdsourcing is a cost-effective method for implementing CDN, but there are complex managerial challenges that should be carefully resolved. They proposed a guiding framework for this purpose along with an auction scheme to resolve the competition between content providers for CDN resources. Furthermore, an attempt at taking advantage of coded caching techniques in crowdsourced CDN has been reported in Reference [184].

Case Studies and Real-World Examples: The literature in the area of CDN comes with some real-world case studies. Among these reports, we can specifically refer to the ones focusing on passive information gathering regarding the implementation details of YouTube's CDN [24, 50]. These studies analyze the CDN of YouTube as a black box and discover how it manages the huge traffic. Some scenarios have been reported in these works where YouTube's CDN is unable to efficiently handle the requested traffic.

3.3 Deployment

Deployment is another almost-uncovered phase of a CDN's lifecycle when it comes to academic research. However, one can refer to a few related works as follows.

ISP-Provider Collaboration: The authors of Reference [55] presented a framework for collaboration between content providers and ISP to deploy a virtual ISP-CDN. They presented some operational parameters to be mentioned in the service level agreements or used in the optimization of virtual ISP-CDN.

Case Studies: There is a research work that focuses on the deployment details of local CDN in China and the way they are connected to global CDN despite limitations in local regulations [175].

3.4 Operation

The operation phase is the fourth phase of a CDN's lifecycle where the CDN is operated and managed to provide its predefined services and run the related applications. Thus, research works regarding CDN applications, services, and management issues of CDN are reviewed under the topic of operation.

3.4.1 Applications. Researchers have considered applications for CDN in the following environments to mention a few.

Mobile Adhoc Networks (MANET): The authors in Reference [66] proposed a CDN overlay on top of a MANET in which the multi-point relays (MPR) play the role of CDN servers. They showed how this overlay CDN can help MANET users deliver content reporting incidents or traffic jams in a city.

Vehicle Monitoring Systems: A CDN architecture was proposed in Reference [173] for processing and storing video captured from vehicles in a vehicle monitoring system. The authors in this report took the real-time requirements of the monitoring system into account in their architecture.

IP TV: A CDN based on SIP/RTSP was designed in Reference [97] for IPTV applications. Another lab prototype of a CND-based IPTV system was reported in Reference [120].

E-Learning: A campus-wide CDN architecture was proposed in Reference [109], which can be used for e-learning purposes. In this report, cache placement and request routing challenges were studied.

3.4.2 Services. The study of different services over CDN has been a research focus in recent years [182]. Most of the research works related to this subject fall into one of the following categories.

Services to Be Provided:

- **Multimedia Streaming:** Multimedia streaming content delivery is probably the best-studied service over CDN. The authors of Reference [140] proposed an architecture for a CDN that is expected to provide a multimedia streaming service. The application of multiple-description coding in multimedia streaming along with the impacts of network topology and packet loss rate on its performance were studied in Reference [10]. A method for overlaying a mobile multimedia streaming CDN on top of existing networks was presented in Reference [166]. Another mobile multimedia streaming framework was introduced in Reference [76], which allows a single web content to be simultaneously downloaded from multiple cache servers.
- **Search:** Search is an obviously required service in every CDN. An algorithm for content search in an indirect trust-based CDN has been proposed in Reference [80].

- **Social Content Delivery:** Content delivery to social networks have been examined in several research works. For example, in addition to the previously discussed studies regarding YouTube [24, 50], the possibility of building a content delivery network to serve a scientific social network such as eScience has been investigated [26, 72]. Moreover, a framework has been presented that makes it possible to divide CDN users into communities on the basis of data gathered from a social network and decide the sever placement/routing strategies accordingly [69].
- **Simultaneous Content-Computation Delivery:** The authors of Reference [32] argued that the capabilities and the performance of a CDN are highly dependent on the underlying network. Moreover, they elaborated on the limited computing capabilities of existing CDN and presented a network architecture that can serve a hybrid content-computation delivery service.

Financial Aspects of Service Delivery: The term service delivery refers to the set of operations required to provide a service to a client by a service provider. Design and improvement of service delivery in CDN has been a research focus in recent years [88]. Studies related to different aspects of service delivery have been reviewed under other topics in previous sections. Here we specifically focus on the works that have investigated cost and pricing, as it is becoming more and more complex with the emergence of new services [56].

The idea of subscription-based CDN was introduced in Reference [162]. In this scheme, providers advertise specific types of content. Users subscribe to their favourite content, and they are charged accordingly. This helps the provider make better decisions in server placement. Moreover, some researchers have proposed bidding as a dynamic pricing mechanisms for content-related services [94].

3.4.3 Management. Management can probably be considered as the least-covered aspect of CDN operation. But still one may refer to a few recent relevant works. For example, a service-specific approach to the management of CDN has been introduced in Reference [137].

3.4.4 Security. The research works reported under this topic have already been reviewed in Subsection 3.1.1. Thus, we do not consider them under the topic of operation, although they are relevant.

3.5 Evaluation

Evaluation is the last phase in the CDN's lifecycle that may suggest a redesign. Under this topic, research works related to monitoring, characterization, and measurement are reviewed as follows.

Monitoring: Monitoring can serve the efficiency of some activities such as server selection in a CDN [108]. An architecture for a CDN monitoring system was presented in Reference [63]. A variant of the latter system was reported in Reference [64], which has been customized to the features of resource-limited applications.

Characterization: Characterizing the behaviour of a CDN can help designers tune the design parameters in the best possible way. This has motivated some research related to the subject. As an example, we can mention the framework presented in Reference [160] for characterizing the probability of resource overloading and packet loss over time in CDN. As another example, one may refer to the characterization of caching workload in CDN reported in Reference [130].

Measurement: Measuring runtime parameters in CDN is another part of the evaluation phase considered by researchers [143]. Moreover, there are some research works that present frameworks for both measurement and characterization. For example, methodologies for measuring and

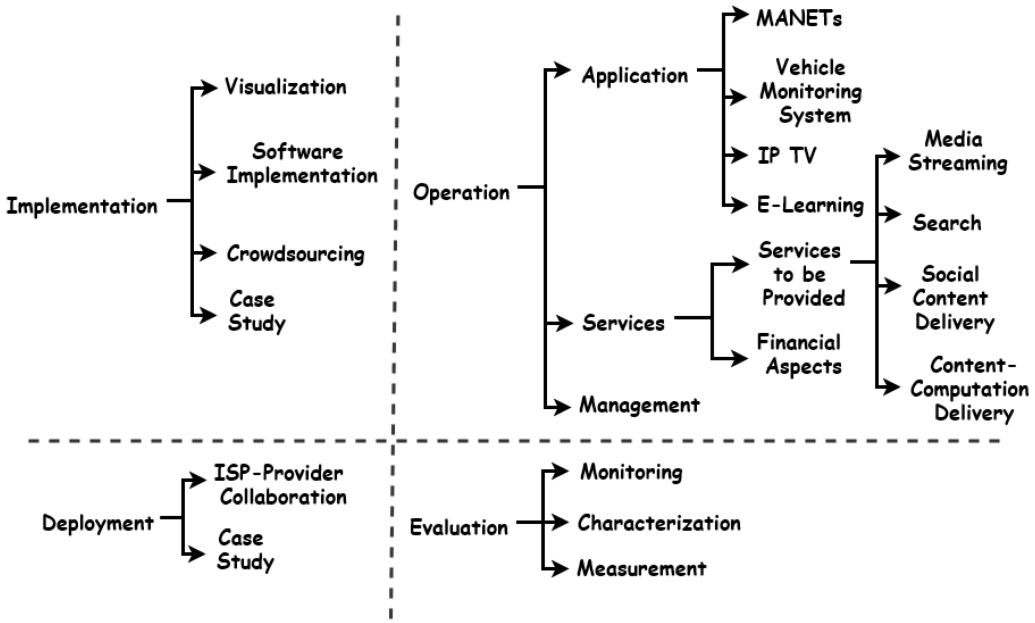

Fig. 8. The classification of research works under the topics of operation and evaluation phases.

characterizing resource utilization, caching performance, and replica consistency in a CDN have been introduced in Reference [75], Reference [131], and Reference [84], respectively.

Figure 8 shows the classification of research reports related to implementation, deployment, operation, and evaluation phases.

4 RESEARCH TRENDS

In this section we make use of the discussions presented in Section 3 to identify existing and emerging research trends in the area of content delivery networks. The identified trends introduced are used to achieve a view to the future of research on CDN. A research trend is a topic that is predicted to be the studied in a lot of research works in the future. This can be decided by the number of existing research works on the topic or other research/technology trends that demand for further research on the topic. The studied trends are encoded for further reference.

4.1 Existing Trends

As expected, most of the existing research trends are related to the design phase of the lifecycle. However, an obvious trend can be identified in the implementation phase. These trends are separately discussed below.

- Existing Trends in the Design Phase
  - **Interaction with Cloud Computing (EXT-01):** It is certainly among the clearest trends in research on CDN as suggested by the discussions in Section 3.1 [29, 40, 81, 110, 125, 165]. This trend is quite likely to be continued as long as new advances keep on emerging research on cloud computing.
  - **Mobile CDN (EXT-02):** This one is another obvious research trend in the field of CDN [18, 76, 85, 166, 179]. As long as mobile networks keep on appearing as the infrastructure

in emerging technologies such as MANET [22, 38] and Vehicular Adhoc Network (VANET) [6, 37], mobile CDN is expected to remain a research focus.
  - **Peering among CDN (EXT-03):** This has been attractive to researchers in this area [21, 112, 113, 156]. The emergence of virtual organizations and similar concepts is a signal for further research on this topic.
  - **Telco CDN (EXT-04):** This kind of CDN have been proposed and studied in Reference [82] and Reference [161]. The fact that telecommunications companies posses edge nodes close to the uses makes CDN-telco a good match and provides a strong philosophical reason for researchers to pay more attention to this match in the future.
  - **Hybrid CDN-P2P (EXT-05):** This trend has its roots in the match between advantages of P2P and CDN [90, 96, 182, 186]. While CDN is seeking performance at the cost of redundant infrastructure, P2P provides cost-effective streaming in large-scale systems. Thus, it is a natural idea to combine the two technologies to achieve both advantages.
  - **CDN as a Service (EXT-06):** This trend has already been started [14, 48, 123], and it is to be continued as several aspects of the idea still need to be investigated.
- Existing Trends in the Implementation Phase
  - **Virtualization and Software Implementation (EXT-07):** Virtualization [92, 168] and software implementation [42, 154] of CDN are ideas borrowed from network and server implementation that aim at cost effective resource allocation. Since the network and servers play critical roles and cost-effective resource allocation is a concern in CDN (refer to Section 3.1), one can easily predict more research to be conducted on these ideas.
- Existing Trends in the Operation Phase:
  - **Social Content Delivery (EXT-08):** Nowadays, a spectrum of people and communities are sharing content over CDN, and this has been considered in academic research [69]. Existing research works on general [24, 50] and scientific [26, 72] social networks built on top of CDN is a research trend.

4.2 Emerging Research Trends

From the review presented in Section 3, the following topics can be extracted as emerging research trends in the field of CDN.

- Emerging Trends in the Design Phase
  - **Hierarchical Design (EMT-01):** Although hierarchical structures have already been considered in different aspects of CDN such as content routing [106], hierarchical CDN architecture design should be considered as an emerging trend [51]. Further research in this regard can be expected because of its impact on the scalability of CDN.
  - **Hybrid CDN-ISP (EMT-02):** This topic has a philosophical reason to remain a hot topic after being introduced and discussed in Reference [167] and Reference [35]; ISP possess edge nodes that are exactly were the CDN caches should be placed.
  - **Virtual Organization (EMT-03):** Virtual organizations are formed as joint ventures among several identities that lead to the implementation of shared peering-based CDN. Although peering has been identified as an existing trend, virtual organization-based CDN [57, 112] should be considered as an emerging trend, as it is not well developed enough.
  - **CDN-Client Interaction (EMT-04):** Research on client peering in CDN [156] and collaborative CDN [47, 117, 177] is quite likely to be continued, as it allows providers to make use of clients' resources.

  - **CDN Internetworking (EMT-05):** This idea has been introduced in Reference [111] and further studied in Reference [19], and it looks promising because of the trend toward peering-based CDN discussed in Section 4.1.
  - **Architecture Design Standard Adoption (EMT-06):** The idea of designing CDN on the basis of multi-tier [4, 53] and Service-oriented Architecture (SOA) [28] models is supported by trends in other branches of technology [121, 136, 152].
  - **Interaction with Vehicular Technology (EMT-07):** The interaction between CDN and vehicular technology has attracted researchers [5, 156, 173], and one can expect more research focus in this area due to the emergence of smart vehicular networks such as VANET [6, 37].
- Emerging Trends in the Implementation Phase
  - **Crowdsourcing (EMT-08):** This is an emerging trend in several branches of technology [58, 164]. It has previously been considered by researchers in the area of CDN [144, 184] and because of its cost-effectiveness, it is anticipated to be further studied in the future.
  - **Coded Caching in CDN (EMT-09):** The authors of Reference [184] have proposed the use of coded caching in crowdsourced CDN. But since coded caching is an existing research trend and CDN is an obvious application of caching, it is pertinent to expect the two research areas to be merged together in the near future.
- Emerging Trends in the Operation Phase
  - **Mixed Computation-Content Delivery: (EMT-10):** This idea has been introduced in Reference [32]. There are two reasons for expecting the idea to be followed by other researchers. First, content delivery is an IO-bounded service, but the edged nodes have grown in intelligence and computing power with the evolution of communication technology and the computational resources in CDN servers, are less utilized than memory and IO devices. Second, the use of distributed caching has already been examined in computational platforms such as Cache Only Memory Architecture (COMA) multiprocessors [43, 132, 133].

4.3 The Future of CDN

The future of CDN can be described using the following headlines.

- **The Convergence of CDN and Fog Computing:** Fog computing (edge computing) is a well-known trend in a variety of technological branches [136, 171]. Interaction between CDN and fog computing platforms has already been proposed [7]. The convergence of CDN and fog computing is an imminent prediction because of a clear philosophical reason explained in the following. Fog computing depends on transferring the computation into edge nodes to reduce the network communication overhead and take advantage of the increasingly growing intelligence and computation power of edge nodes due to advances in communication technology. However, edge nodes are well equipped in CDN. Thus, it is pertinent to place computation on CDN edge servers.
- **The Interaction between Fog Computing and Machine Learning:** Fog computing requires some auxiliary techniques for smart placement of computation on proper edge nodes. This need is predicted to be fulfilled via interaction with machine learning and deep learning [25].
- **Machine learning in CDN:** The above two paragraphs suggest an imminent convergence between CDN and machine learning. Machine learning [25] and deep learning [126] have already been considered by researchers in recent years as approaches to improving the performance of the caching system in CDN via proper selection of the contents to be cached.

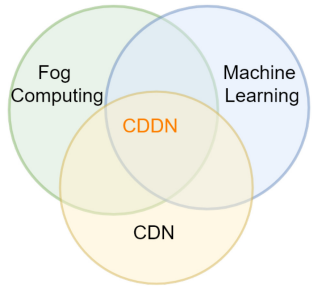

Fig. 9. Content development and delivery network.

Different popularity prediction methods based on machine learning have been presented [54]. Several other aspects of these approaches have been studied in recent research works [17, 68, 79].

- **Content Development in CDN:** As explained under the topic of trend EMT-10, content delivery tends to be mixed with computation in CDN. Among different kinds computations that can be undertaken by CDN, one can refer to content development process. This process is predicted to be decentralized by being moved from central data centres and server farms outside the CDN to CDN edge servers.
- **Support of Telecommunications Operators and the Technology:** As mentioned in trends EXT-04 and EMT-02, big ISP and operators are increasingly investing on the deployment of CDN edge servers that increases the number and processing power of these servers and makes edge computing in CDN more and more feasible. This tendency is supported by advances in telecommunication technology and especially mobile communication technology. Specifically, 5G-CDN looks an attractive match [87, 147]. There has been an extensive research effort toward this match in recent years [31, 73]. Different technical aspects of this topic have been studied among which one can refer to efficient scheduling [30, 31], delay improvement [180], interaction with satellite and terrestrial networks [11, 73, 99], multimedia delivery [119, 122] and service delivery model optimization [89].

The convergence of CDN, fog computing and machine learning characterizes Content Development and Delivery Network (CDDN) as the future of CDN. Figure 9 shows CDDN as the result of this convergence. In a CDDN, content is both developed and delivered to the end user by edge servers. Machine learning and deep learning mechanisms make it possible to predict the future demands for contents and to place the contents and the corresponding development processes accordingly.

To give an image of the future of CDN, one should consider the trends mentioned in Section 4 in addition to the implications of CDDN. Compared to the traditional architecture of a CDN shown in Figure 1, Figure 10 shows the future view to a CDN from the perspective of a content provider according to the existing and emerging trends mentioned above. Figure 10 reflects trends EXT-01, EXT-02, EXT-03, EXT-04, EXT-06, EXT-08, EMT-03, EMT-04, EMT-05, EMT-07, and EMT-10.

5 WHERE WE SHOULD BE HEADED

In the field of CDN, an executive orientation can be clearly seen even in research reports, which implies that academia is currently following and not leading the technology trends. This leads to lack of academic coverage in some conceptual and theoretical aspects of the technology. Discovering these aspects clarifies future directions to be taken by researchers. Some of these aspects are discussed in the following.

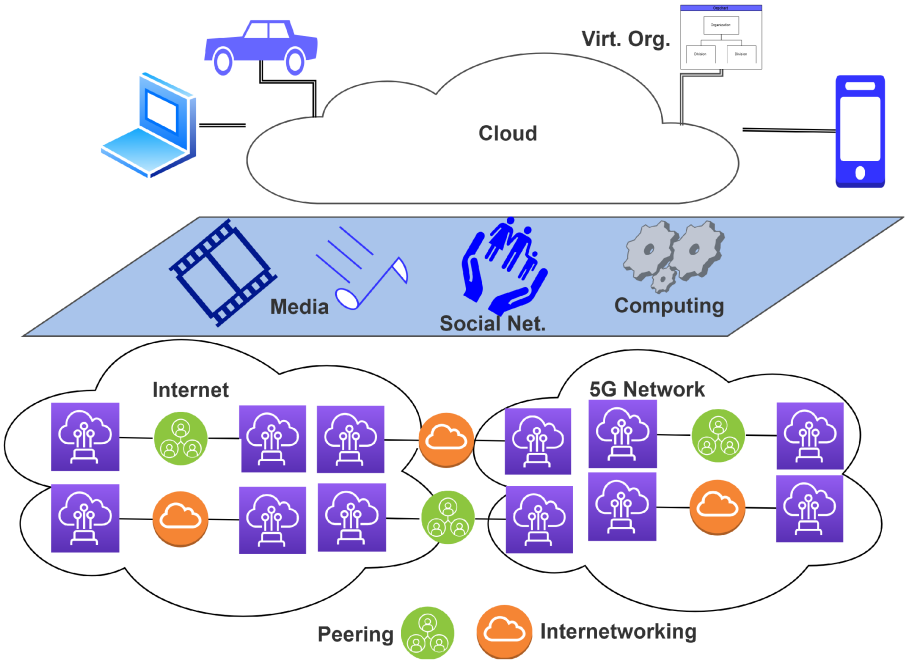

Fig. 10. The future view of CDN.

First, the terminology of the field should be standardized. Currently, there is a glaring inconsistency between names and terms used in the area. For example, one can see the terms *Cache Server* and *Edge Server*, *Surrogate Server*, and *Request Server* or *Content Server* and *Origin Server* used for the same concepts. Even the term CDN technology itself is sometimes referred to as *Content Distribution Network* instead of *Content Delivery Network*. Standardizing the terminology requires the existing terminology to be collected first. Then the most proper terms should be selected or even invented for each concept or phenomenon.

In the second step, the position of the research area in scientific subject classifications should be clearly defined. For example, a topic or subtopic needs to be assigned to the subject in ***ACM CCS Concepts***.

In the next step, the lifecycle of a CDN should be standardized. This helps the related research topics to be classified in the first level. However, we refer to the lifecycle shown in Figure 3 in the absence of a standardized one.

Before elaborating on future research guidelines, let us present some statistical information on existing research related to each of the phases in the CDN lifecycle. Table 3 summarizes this information.

In Table 3, $L1$ through $L7$ represent the levels of the classification. Further, T and P in each level represent the numbers of topics and research reports, respectively.

Now let us continue by discussing what should be done to make the design phase of the CDN lifecycle academically more mature. The design issues, challenges, and principles should be studied thoroughly. As seen in Figure 4, this branch of the classification tree is far from expectations in terms of depth and density. Without such thorough research, there cannot be dependable design frameworks, and it will be impossible to test and evaluate a design. Furthermore, as suggested by Figure 5, one can mention architecture design as another topic that needs to be further examined.

Table 3. Statistical Information on Existing Research Works Related to CDN

Phase	Levels													
	L1		L2		L3		L4		L5		L6		L7	
	T	P	T	P	T	P	T	P	T	P	T	P	T	P
Des.	3	0	8	0	15	4	25	8	34	72	23	15	5	16
Impl.	4	8	0	0	0	0	0	0	0	0	0	0	0	0
Depl.	0	2	0	0	0	0	0	0	0	0	0	0	0	0
Oper.	4	1	9	5	4	14	0	0	0	0	0	0	0	0
Eval.	3	9	0	0	0	0	0	0	0	0	0	0	0	0

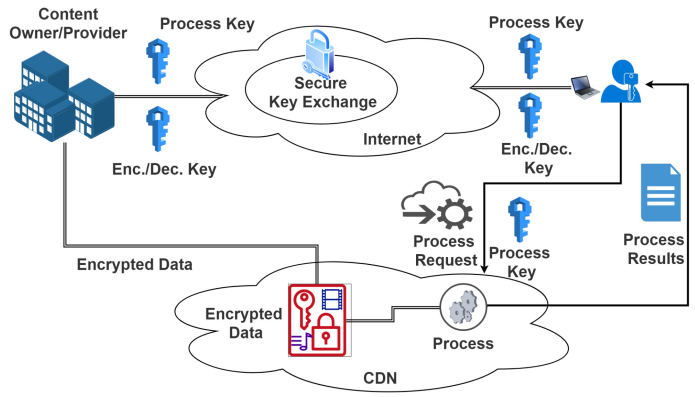

Fig. 11. Homomorphic encryption for improving privacy in CDN.

A simple comparison between security-related research in CDN and some other technologies highlights a critical need for more research on CDN security. For example, Distributed Denial of Service (DDoS) protection requires serious investigation as CDN are closely interacting with users. However, not only CDN need to be protected: Users and businesses should be secured against malicious CDN. For example, privacy issues such as consent management require more effort, because users have access to behavioural information regarding users. Recent advances in information security and privacy such as homomorphic encryption [20, 86] should be followed to improve privacy in CDN. Homomorphic encryption allows data to be encrypted in a way that it can be processed as if it has been decrypted, processed, and encrypted again. When it comes to some services such as content search, research in homomorphic encryption is certainly mature enough to support research in CDN privacy [169]. But this will require some interaction between the end user and the content owner/provider. Figure 11 shows such a solution. Furthermore, copyright mechanisms such as watermarking should be studied and standardized as contents shared over CDN are business values to providers. The latter mechanisms have been well studied in branches such as digital cinema [65, 78, 135]. Thus, the achievements of research in those branches can be used to improve copyright preservation in CDN. Security should be considered in each phase of the lifecycle.

As suggested in Subsection 3.4.3, management is the next facet of the technology that requires a serious effort. Management should include every aspect in each phase of the lifecycle. The same goes with standardization. Moreover, Figure 4 suggests a comprehensive research on the standardization of CDN. In fact, several aspects in each phase the CDN lifecycle need to be standardized. To mention a few, architecture, communications, routing, and media coding are among these aspects.

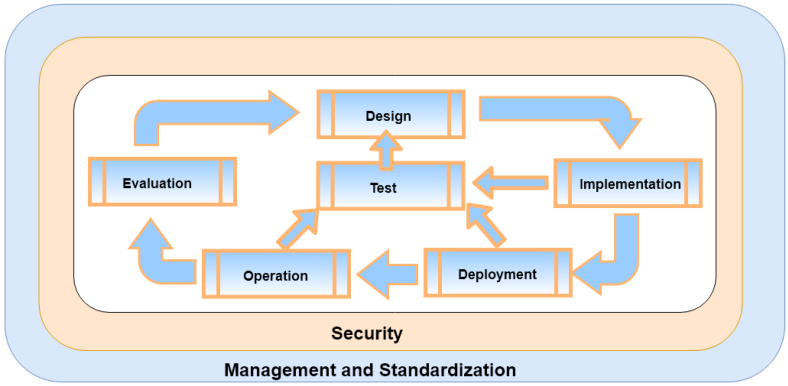

Fig. 12. The future lifecycle of a CDN.

The discussions in Section 3.3 clearly highlight deployment as a less-studied phase in the lifecycle of a CDN. The considerations and principles of this phase should undergo thorough research.

According to the above discussions, we expect the future lifecycle of a CDN to be as shown in Figure 12.

6 CONCLUSIONS

In this article, we highlighted the fact that the industry has moved faster than academia in the area of content delivery networks. We classified the existing academic research reports in this area in a way that suggests a lifecycle for CDN. Then we used the classification to highlight existing and emerging research trends in the area. Moreover, we outlined the aspects of the technology that have been left uncovered or less covered by the academic research. This study sheds light on the directions that should be pursued by the research community to overcome the remaining challenges and support the advances in the technology. Our work in this article can be continued by research in the directions given in Section 5.

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