Security, Privacy, and Access Control in Information-Centric Networking: A Survey

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***Abstract*—Information-Centric Networking (ICN) replaces the widely used host-centric networking paradigm in communication networks (e.g., Internet and mobile ad hoc networks) with an information-centric paradigm, which prioritizes the delivery of named content, oblivious of the contents' origin. Content and client security, provenance, and identity privacy are intrinsic by design in the ICN paradigm as opposed to the current host centric paradigm where they have been instrumented as an after-thought. However, given its nascency, the ICN paradigm has several open security and privacy concerns. In this article, we survey the existing literature in security and privacy in ICN and present open questions. More specifically, we explore three broad areas: security threats, privacy risks, and access control enforcement mechanisms.**

We present the underlying principle of the existing works, discuss the drawbacks of the proposed approaches, and explore potential future research directions. In security, we review attack scenarios, such as denial of service, cache pollution, and content poisoning. In privacy, we discuss user privacy and anonymity, name and signature privacy, and content privacy. ICN's feature of ubiquitous caching introduces a major challenge for access control enforcement that requires special attention. We review existing access control mechanisms including encryption-based, attribute-based, session-based, and proxy re-encryption-based access control schemes. We conclude the survey with lessons learned and scope for future work.

***Keywords*–Information-centric networking, security, privacy, access control, architecture, DoS, content poisoning.**

1. Introduction

According to the Cisco Visual Networking Index forecast, video traffic (including VoD, P2P, Internet, and TV) will comprise 90% of all Internet traffic by 2019[1]. The majority of this traffic is currently served to end users with the help of content delivery networks (CDNs), with servers that reside close to the network edge. This has helped reduce core network traffic and improve delivery latency. Despite the scalability that CDNs have so far provided, the current host-centric paradigm will not continue to scale with the proliferation of mobile devices and the Internet of Things (IoTs) coupled with the rapidly increasing volume of video traffic. In the IoT domain, every node can be a provider. This results in several many-to-many communications, which increases the size of routing tables and requires maintenance of per node multicast trees, thus undermining scalability. Not only have these trends been putting pressure on Internet Service Providers (ISPs) and content providers, but they have also motivated the research community to explore designs for a more scalable Internet, with a primary objective of efficient content delivery. One of the products of this endeavor is the Information-Centric Networking (ICN) paradigm [1]–[3].

ICN shifts the networking paradigm from the current host-centric paradigm, where all requests for content are made to a host identified by its IP address(es), to a content-centric paradigm, which decouples named content objects from the hosts where they are located. As a result, named content can be stored anywhere in the network, and each content object can be uniquely addressed and requested. Several ICN architectures such as Named-data networking/content-centric networking (NDN/CCN) [1], Publish-Subscribe Internet Routing Paradigm (PSIRP) [2], Data Oriented Network Architecture (DONA) [4], and Network of Information (NetInf) [5] have been proposed. Though they differ in their details, they share several fundamental properties: unique name for content, name-based routing, pervasive caching, and assurance of content integrity. ICN enhances several facets of user experience as well as security, privacy, and access controls. However, it also gives rise to new security challenges.

In this article, we explore ICN security, privacy, and access control concerns in-depth, and present a comprehensive study of the proposed mechanisms in the state of the art. We categorize this survey into three major domains, namely security, privacy, and access control. In the security section, we address *denial of service* (DoS and distributed DoS or DDoS) attacks and vulnerabilities unique to ICN, including *cache pollution*, *content poisoning*, and *naming attacks*. Despite many similarities between a classical DoS attack and the DoS attack in ICN, the latter is novel in that it abuses ICN's stateful forwarding plane. The attack aims to overload a router's state tables, namely the pending interest table (PIT). The cache pollution attack targets a router's content locality with the intention of altering its set of cached content resulting in an increase in the frequency of content retransmission, and reduced network goodput.

This work was supported in part by the U.S. NSF grants:1719342, 1345232, and 1248109 and the U.S. DoD/ARO grant: W911NF-07-2-0027. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Federal Government.

[1]Cisco Visual Networking Index:Forecast and Methodology

In the privacy section, we study the privacy risks in ICN under four classes: *client privacy*, *content privacy*, *cache privacy*, and *name and signature privacy* [6]. We explore the implications of each of these risk classes and elaborate on relevant proposed solutions. Due to ICN's support for pervasive caching, content objects can be replicated throughout the network. Though this moves content close to the edge and helps reduce network load and content retrieval latency, it comes at a cost—publishers lose control over these cached copies and cannot arbitrate access. Thus, there is need for efficient access control, which allows reuse of cached content and prevents unauthorized accesses.

Access control mechanisms based on *content encryption*, *clients' identities*, *content attributes*, or *authorized sessions* have been proposed in the literature. We review these proposed mechanisms and highlight their benefits and drawbacks in detail in the access control section. In the three domains, we present a summary of the state of the art and also discuss open research challenges and potential directions to explore. We conclude the survey with a summary of lessons learned.

Before we dive into the discussion, we briefly review some representative ICN architectures in Subsection 1.A. Following that we identify previous surveys in ICN covering different ICN architectures, naming and routing, DoS attacks, mobility, and potential research directions in Subsection 1.B.

A. Overview of the Proposed Information-Centric Networking Architectures

In this subsection, we review some representative ICN architectures including DONA [4], CCN [1], [7], NDN [8], PSIRP/PURSUIT [2], [9], [10], NetInf [5], and MobilityFirst [11], [12]. We refer interested readers to two surveys [13], [14] for more details on other ICN architectures, such as SAIL [15], 4WARD [16], COMET [17], [18], CONVERGENCE [19], and CONET [20]. In this survey, we will focus on research relevant to three architectures in particular, namely CCN [1], [7], NDN [8], and PSIRP/PURSUIT [2], [9], [10]. These three have received the most attention from the community in the past and continue to be favored as architectures of choice.

The *Data Oriented Network Architecture* (DONA) [4] was proposed by Koponen *et al.* at UC Berkeley in 2007. DONA uses a flat self-certifying naming scheme. Each name consists of two parts; the first is the cryptographic hash of the publisher's public key, and the second is an object identifier, which is assigned by the publisher and is unique in the publisher's domain. To achieve self-certification, the authors suggested that publishers use a cryptographic hash of the object as the object identifier. A subscriber can then easily verify the integrity of an object simply by hashing it and comparing the result to the object's name. DONA's resolution service is composed of a hierarchically interconnected network of resolution handler (RH) entities, which are tasked with publication and retrieval of objects.

To publish an object, the owner sends a *REGISTER* message including the object name to its local RH. The local RH, keeps a pointer to the publisher and propagates this message to its parent and peer RHs, who then store a mapping between the local RH's address and the object name. A subscriber interested in the object sends a *FIND* message with the object name to its own local RH. The local RH propagates this request to its parent RH. The propagation continues until a match is found somewhere in the hierarchy.

After finding a match, the request is forwarded towards the identified publisher. The authors proposed two methods of object delivery from a publisher to a requester. In the first method, the publisher sends the object using the underlying IP network. The second method takes advantage of path symmetry: the request message records the path it takes through the network. After reaching the publisher, the object traverses the reverse path from the publisher to the requester. Exploiting this routing model, RHs on the path can aggregate the request messages for an object and form a multicast tree for more efficient object dissemination/delivery.

Content-centric Networking (CCN) [1], [7] was proposed by researchers at Palo Alto Research Center in 2009. In 2010, *Named Data Networking* (NDN) [8], which follows the same design principles, was selected by the US National Science Foundation (NSF) as one of four projects to be funded under NSF's Future Internet Architecture program. Both CCN and NDN share the same fundamentals, such as a hierarchical naming scheme, content caching, and named content routing (NDN was CCN before it branched out). The hierarchical naming allows the provider's domain name to be used in making routing decisions. In the client-driven CCN/NDN, a client sends an interest packet into the network to request a content by its name.

Routers, equipped with a content store (CS), a pending interest table (PIT), and a forwarding information base (FIB), receive the interest and perform a CS lookup on the content name. If the content is not available in the CS, the router performs a PIT lookup to check whether there is an existing entry for the requested content. If the PIT lookup is successful, the router adds the incoming interest's interface to the PIT entry (interest aggregation) and drops the interest. If no PIT match is found, the router creates a new PIT entry for the interest and forwards the interest using information from the FIB.

An interest can be satisfied either by an intermediate forwarding router which has cached the corresponding content chunk, or the content provider. In both cases, the content takes the interest's reverse-path back to the requester. Upon receipt of a content chunk, a router forwards the chunk along the interfaces on which it had received the corresponding interests for the chunk. The router may cache a copy of the content in its CS in addition to forwarding it through the designated faces.

The *Publish Subscribe Internet Technology* (PURSUIT) [10] project and its predecessor *Publish Subscribe Internet Routing Paradigm* (PSIRP) [2], [9], were funded by FP7 (European Union's research and innovation program) to produce a publish-subscribe protocol stack. A PURSUIT network is composed of three core entities, namely Rendezvous Nodes (RNs) which form the REndezvous NEtwork (RENE), the topology manager,

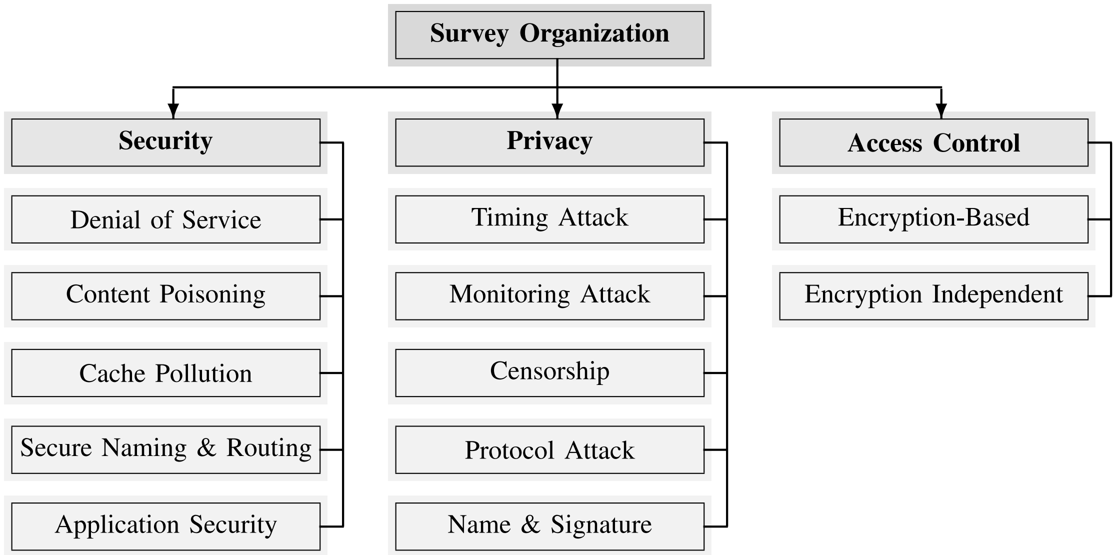

Fig. 1: The organization of the survey.

and forwarders. Similar to DONA, PURSUIT uses a flat naming scheme composed of a scope ID, which groups related information objects, and a rendezvous ID, which ensures that each object's identifier is unique in its group. A publisher advertises its content by sending a *PUBLISH* message to its *local RN* (the RN in the publisher's vicinity), which routes the message to the RN designated to store the content name defined by the scope (*designated RN*). The local RN makes this decision using a distributed hash table (DHT). A subscriber interested in the content object sends a *SUBSCRIBE* message to its local RN, which will also be routed to the designated RN using the DHT.

Upon receipt of a *SUBSCRIBE* message by the designated RN, the topology manager is instructed to generate a delivery path between the publisher and the subscriber. The topology manager then provides the publisher with a path through the forwarders. In PURSUIT, network links are each assigned a unique string identifier, which the topology manager uses to create a routing Bloom filter for each flow. The generated Bloom filter is then added to each packet's header, and is used by the intermediate forwarders for content delivery.

Network of Information (NetInf) [5] was initially conceived in the FP7 project 4WARD [16]. NetInf employs a flat naming scheme with a binding between names and their locators, which point to the content's location. As several nodes can cache copies of the data, an object may be bound to more than one locator. Two models of content retrieval are offered by NetInf: name resolution and name-based routing. In the name resolution approach, a publisher publishes its data objects to the network by registering its name/locator binding with the name resolution service (NRS). An interested client resolves the named data object into a set of locators and subsequently submits a request for the object, which will be delivered by the routing forwarders to the best available cache.

The routing forwarders, after obtaining the data, deliver it back to the requester. In the name-based routing model, a client directly sends out a *GET* message with the name of the data object. This message is forwarded to an available storage node using name-based routing, and the data object, once found, is forwarded back to the client.

MobilityFirst [11], [12] was funded by the NSF's future Internet Architecture program in 2010. The main focus of this architecture is to scale in the face of device mobility, hence it includes detailed mechanisms for handling mobility, wireless links, multicast, multi-homing, security, and in-network caching. Each network entity (including devices, information objects, and services) is assigned a globally unique identifier (GUID), which can be translated into one or more network addresses. To advertise a content, a publisher requests a GUID from the naming service and registers this name with a global name resolution service (GNRS).

The registered GUID is mapped, by a hash function, to a set of GNRS servers, which are connected through regular routing. A subscriber can then obtain the content name from a Name Certification Service (NCS) or use a search engine to resolve a human-readable name into the corresponding GUID. A subscriber submits a *GET* message, containing both the GUID of the desired object and its own GUID, to its local router. Since routers require the network address, the request will be forwarded to the GNRS to map the GUID into actual addresses. The result of this query is a set of partial or complete routes, or a set of addresses.

Upon receiving this information, the requesting router attaches the destination network address to the *GET* message and forwards it into the network. Any router on the forwarding path may contact the GNRS for an updated destination address or route; routes may change due to events, such as provider's mobility, congested link, and link failure. The publisher, upon receiving the *GET* message, sends the requested object back to the source GUID following the same procedure. MobilityFirst provides a combination of IP routing and name-based routing

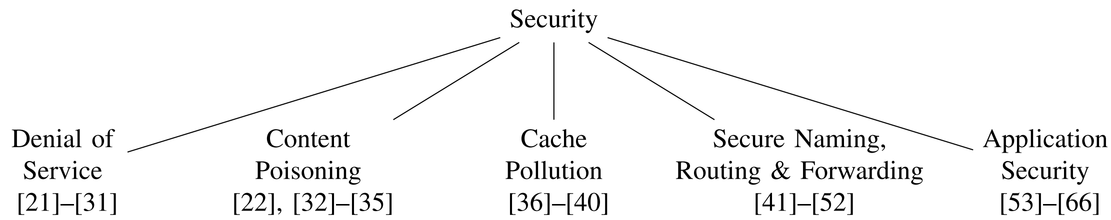

Fig. 2: ICN security sub-categories and the state-of-the-art.

by name resolution and data routing processes. On-path caching is employed to satisfy subsequent requests for previously served GUIDs. This is in contrast to off-path caching, which causes an update in the GNRS service, where the new caching node's network address is added to the GUID's record.

B. Review of Existing ICN Surveys and Overview Literature

Ahlgren *et al.* [13] reviewed the different proposed information-centric architectures. In addition to describing the architectures in detail, the authors also presented their open challenges. Following this survey, Xylomenos *et al.* [14] surveyed the proposed ICN architectures, comparing their similarities and differences, and discussing their weaknesses. Tyson *et al.* focused on mobility in information-centric networks in [67]. Several benefits of node mobility were discussed by the authors, as well as mobility-related challenges such as provider mobility and cached content discovery. Zhang, Li and Lin [68] and Zhang *et al.* [69] explored proposed caching approaches in information-centric networking. In [70], Bari *et al.* reviewed the state-of-the-art in naming and routing for information-centric networks and explored the requirements for ideal content naming and routing. Future research directions in information-centric networking were discussed by Pan *et al.* [71].

Aamir and Zaidi [72] surveyed denial-of-service attacks in information-centric networks and identified interest flooding, request piling, content poisoning, signature key retrieval, and cache pollution as DDoS vectors. AbdAllah *et al.* [73] recently discussed security attacks in ICN. The authors classified attacks into four categories: routing, naming, caching, and miscellaneous. The paper focused on discussing the ways an attacker can orchestrate these attacks as well as the applicability of current IP-based solutions to information-centric networks.

In other overview work, Marias *et al.* [74] identified security and privacy concerns in a future Internet architecture. They reviewed physical layer security, network coding security, and network infrastructure security literature and identified authentication and identity management as core building blocks of a secure network, and discussed implementation challenges. However, the authors did not elaborate on the attacks that are inherent to ICN, such as cache pollution, content poisoning, DoS/flooding, and the timing attack. Furthermore, a review of existing access control mechanisms for ICN has been neglected. Wahlisch *et al.* [75] discussed the threats and security problems that arise due to stateful data planes in ICN. The authors categorized these attacks into three classes: resource exhaustion, state decorrelation, and path and name infiltration. Despite presenting a thorough attack classification, this paper did not discuss any mitigation to the aforementioned attacks.

In [76], Fotiou *et al.* discussed the security requirements and threats in pub/sub networks including client privacy, access control, content integrity, confidentiality, and availability, and subscriber and publisher authentication, and user subscription anonymity. However, they did not propose any solutions. Loo *et al.* [77] studied the security challenges faced by the NetInf architecture from the perspectives of both applications and infrastructure. The authors divided their concerns into eight categories: access control, authentication, non-repudiation, data confidentiality, data integrity, communication security, availability, and privacy. However, the descriptions of the problems and proposed solutions are at a high level and lack details or scope of future challenges.

Novel Contributions of this Survey: All the existing surveys have either not dealt with security, privacy, and access control or have looked at them to a very limited extent. The work of AbdAllah *et al.* [73] is the first survey dealing with security in ICNs, but it is not comprehensive. The survey deals more with the generic security concerns, without covering the ICN-specific body of the work in depth. Also, access control in ICNs has not be considered in any survey. *To the best of our knowledge, we are the first to present a comprehensive survey of the state-of-the-art in security, privacy, and access control in the context of ICN.* We present each of these three aspects independently, surveying the state of the art, lessons learned, and the shortcomings of proposed approaches. We also discuss existing challenges and propose potential directions and solutions.

The rest of the paper is organized as depicted in the Fig. 1. As depicted in the figure, we classify the state of the art in security and privacy in terms of attacks and corresponding proposed mitigations. As for access control, we divide the state of the art in terms of the mechanism used in the proposed solutions, which either address authentication and/or authorization. In Section 2, we review the security issues of different ICN architectures, their proposed solutions, and existing open problems. Different privacy issues, proposed solutions, and open challenges are presented in Section 3. Access control enforcement mechanisms, their drawbacks, and existing open challenges are presented in Section 4. In Section 5, we summarize the state of the art and present a comprehensive discussion of future research directions.

2. Security in ICN

In this section, we review vulnerabilities in ICN and discuss the state-of-the-art solutions, then conclude this section with open problems and potential solutions to be explored. This section is divided into subsections based upon the particular types of attacks. In Fig. 2, we show our categorization of the state of the art in security research. We divide the literature in the state of the art into six categories based on the particular attack and its mitigation approaches: DoS; content poisoning; cache pollution; secure naming, forwarding, and routing; application security; and other general contributions (i.e., contributions that cannot be grouped into one of the above specific subcategory). In the following subsections, we discuss each of these subcategories in detail in the order they appear here.

A. Denial of Service (DoS) Attack

DoS attacks aim to overwhelm the network services by inundating them with requests; e.g., server(s) inundated with requests for service (content, domain name queries, etc.) [78]–[80]. In ICN, DoS attacks may target either the intermediate routers or the content providers. The most basic type of attack, interest flooding, involves an attacker sending interests for a variety of content objects that are unlikely to exist in the targeted routers' caches. This attack applies to pull-based (consumer-driven) architectures such as CCN/NDN, DONA, and NetInf, where the intermediate entities are the attack targets (e.g., PIT in CCN/NDN, RH in DONA, and NRS in NetInf).

The attack scenario in CCN/NDN is depicted in Fig. 4, which shows clients and an attacker connected to an edge router, which can cache content. The network is composed of a content provider at one end (on the right) and the routing core consisting of routers without content cache and the routers with content cache. In this scenario, the edge router connected to the attacker as well as legitimate clients has its PIT filled up disproportionately by the attacker's interests. The interest name */attack/C** refers to some undefined content name that may not exist, is inaccurate, or is a request for dynamic content to be created on-the-fly.

This attack is more severe when the attacker requests fake content objects (i.e., names with a valid prefix and an invalid suffix) or dynamic objects, which need to be generated by the provider on demand. Requests for fake objects will result in the provider dropping the interest; while the PIT entries on the targeted router(s) (e.g., routers on the path) will only get purged on expiration (expiration time can be large for interests). On the other hand, dynamic content requests will have to be served by the provider. However, these requests/replies burden the forwarding routers as well as they may not be aggregated (most dynamic content is not popular), and may also cause DoS at the provider.

Fig. 3 illustrates the DoS countermeasures categorization. We categorize the research in DoS mitigation into three broad categories: *rate limiting* approaches in which a router mitigates DoS attacks by throttling interests it receives from its downstream neighbors; *statistical modeling* approaches, where a node detects DoS by using statistical information on PIT occupancy. The last category includes several approaches that include using stateless forwarding and client's proof-of-work.

*1) **Rate Limiting-Based Countermeasures**:* A large body of literature exists on rate limiting-based DoS mitigation approaches in which a router detects a DoS attack by monitoring the timeout rates of interests on its faces and/or size of its PIT occupied with interests. When attack is detected a router limits the interest arrival rate on its suspicious faces. We subcategorize the rate limiting approaches further into per-face information monitoring and PIT size monitoring approaches.

a) Per-Face Monitoring Approaches: In general, in the per-face monitoring approaches, a router stores information, such as the number of timed-out interests and the ratio of incoming interests to outgoing content. Using the collected information, the router detects an ongoing attack and mitigates it by rate limiting the faces through which it receives malicious interests.

Afanasayev *et al.* [21] proposed three approaches to coping with interest flooding attacks in NDN. Their vanilla approach is a slight modification of the well-known Token Bucket algorithm, in which each router limits the number of pending interests for each interface proportional to its uplink capacity (bandwidth-delay product). This technique cannot differentiate between an attacker and a legitimate user's interests. Hence an attacker can commandeer the entire uplink capacity with its interests, hence reducing the satisfaction rate of legitimate clients' interests.

The authors augmented this vanilla approach by introducing a concept of per-interface fairness, where the outgoing link capacity is shared fairly among traffic from all incoming interfaces (each incoming interface has its own queue). This prevents traffic from a minority of incoming interfaces from consuming the entire link capacity. An interface with a high interest arrival rate is subjected to packet queuing for fairness. This approach improves fairness, but there is still no distinction between an attacker and a legitimate client.

The last proposal differentiates interest timeout events from interest satisfaction events. Each router gives the interfaces with higher satisfaction rates a greater share of the outgoing link capacity. However, this approach can unduly penalize interfaces that have interests that follow a larger path length. The greater the path length, the larger the probability of congestion and interest drops, which reduces the satisfaction rate of the corresponding interface. Also, with more routers along the path the probability of rate limiting of a flow increases. To address this drawback, the authors suggested that routers explicitly announce their interest satisfaction ratio limits to their downstream neighbors, who can accordingly adjust their own acceptance thresholds. This algorithm, despite being more effective, still applies penalties at the granularity of interface, not flow. Legitimate users' flows will still suffer.

Gasti *et al.* [22] also explored DDoS attack scenarios in

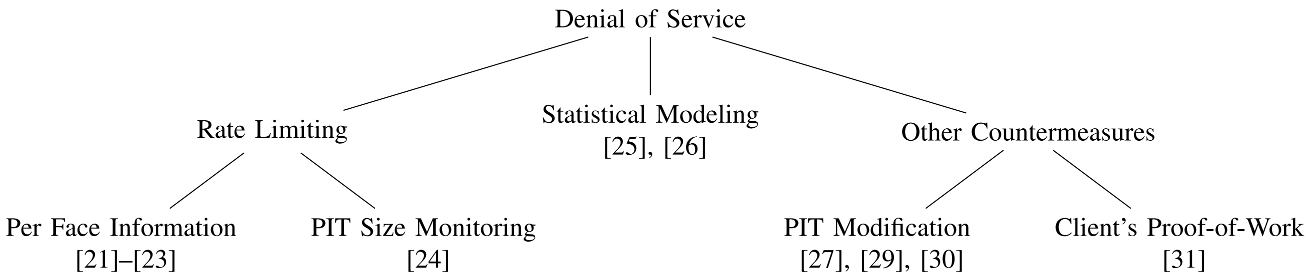

Fig. 3: Denial of Service countermeasure sub-classes and the state-of-the-art.

NDN, focusing primarily on interest flooding. The authors divided interest flooding scenarios into classes depending on whether the attackers request (1) existing or static, (2) dynamically generated, or (3) non-existent content objects. The attack target for Types (1) and (3) is only the network-core infrastructure, while the Type (2) attack targets both content providers and the network-core. The authors noted that malicious requests for existing or static content has limited effect due to content caching at intermediate routers.

In contrast, requesting dynamically generated content not only consumes intermediate routers' resources (such as PIT space and bandwidth), but also keeps the providers busy. It was noted that non-existent content is the type most likely to be used in attacks against infrastructure. To mitigate the attack, the authors suggested that routers keep track of the number of pending interests per outgoing face, as well as the number of unsatisfied interests per incoming face and/or per-name prefix. Rate limiting is applied when these counters exceed a predefined threshold. We note that the per-name prefix based rate limiting is a better approach than per-interface rate limiting.

Compagno *et al.* [23] designed Poseidon, a collaborative mechanism for interest flooding mitigation. Poseidon involves two phases: detection and reaction. Detection is performed individually at the router which monitors two values over a time window: ratio of incoming interests to outgoing content, and the amount of PIT state consumed by each interface. When a pre-set threshold is reached the router invokes the collaborative mitigation mode. The router rate limits its interfaces with

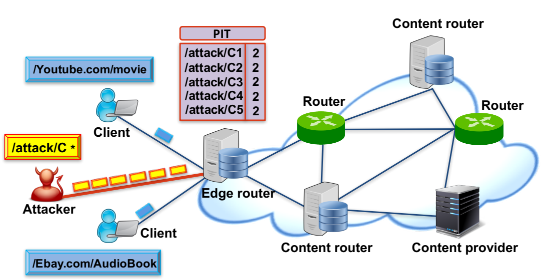

Fig. 4: Denial of Service (DoS) attack scenario: The attacker fills-up the edge router's PIT with a disproportionate number of requests.

abnormal interest arrival rates and sends attack notification to its downstream routers. This helps downstream routers to detect the attack at an earlier stage.

The authors noted that rate-limiting was more effective at reducing the attacked router's PIT size than the notification mechanism, however notification improved the satisfaction rate of requests. This mechanism also does not address the differentiation between the attacker and the legitimate user. Legitimate clients collocated on the same interface with an attacker can be adversely affected.

b) Approaches that Monitor PIT Size: PIT size growth rate can be used to detect DoS attacks as well. In most of the proposed approaches, a router constantly monitors the size of its PIT. If the PIT size reaches a threshold, the router enters the mitigation phase.

Dai *et al.* [24] proposed an approach inspired by the IP-traceback approach for mitigating interest flooding. The scheme allows an attack to be "traced back" to the attacker. The *interest traceback* procedure is triggered when a router's PIT size exceeds a predefined threshold. On trigger, the router generates a spoofed data packet for the longest-unsatisfied interest in the PIT. The spoofed data will be forwarded to the attacker, causing its edge router to be notified of the malicious behavior; in response, the edge router can rate-limit the attacker's interface.

Similar to other rate-limiting approaches, this mechanism may also have a negative impact on legitimate clients. A legitimate client that mistakenly requests a non-existent (or yet-to-be-created) content, will be unfairly penalized. Additionally, since rate limiting only occurs at the edge router, this scheme may be ineffective if an edge router is compromised or is non-cooperative with its peers.

*2) **Statistical Modeling-Based Countermeasures**:* The statistical modeling-based approaches rely on statistical information of a router's PIT and interfaces to identify an abnormal traffic pattern. For instance, Wang *et al.* [25] proposed an interest flooding detection and mitigation mechanism based on fuzzy logic and routers cooperation. In the detection part, the core routers monitor their *PIT Occupancy Rate* (POR) and *PIT Expiration Rate* (PER), which represent the rate addition of new entries into a PIT and the rate of PIT entry expiration, respectively. The collected real-time POR and PER values are used through fuzzy inference rules to identify if they are normal or abnormal.

If either value is abnormal, the router triggers a mitigation mechanism. The router identifies the targeted prefix and the interface on which the most interests for that prefix have arrived; applies rate-limiting to that interface; and notifies its downstream neighbor on the interface of the targeted prefix for more rate control. Simulation results show the schemes' effectiveness in reducing PIT memory consumption and increasing legitimate interest satisfaction. However, the assumption that the attackers only target a specific name prefix makes mitigation only effective in dismantling attacks against specific publishers not against the network infrastructure itself. Moreover, a distributed DDoS attack is still feasible.

Nguyen *et al.* proposed an interest flooding detector based on statistical hypothesis testing theory [26]. The scheme is based upon the fact that when under attack, the interest rate on an interface is greater than that during normal conditions. Meanwhile, the data rate under both hypotheses remains the same; therefore, the data hit-ratio in attack scenarios is lower than that in normal conditions. Unlike other solutions, this scheme takes the desired false alarm probability as a parameter and calculates the detection threshold accordingly. However, the evaluation uses only a simple binary tree graph with eight clients and one attacker. The effectiveness of the scheme for larger networks or during distributed attacks is difficult to analyze.

3) ***Other Countermeasures****:* This category of DoS mitigation includes approaches that change routers' structures, such as PIT and content store, or inherently reduce the clients' request rates by requesting proof-of-work.

a) Approaches that Modify Router's PIT or Cache: The approaches in this category focus on DoS attacks targeting the routers' PITs. The solutions proposed include augmenting the routers with bigger PIT, longer caching period, and removing suspicious interests from routers' PITs. For instance, Wang *et al.* [27] investigated the effect of content caching on DoS attacks, focusing on CCN in particular. They compared the DoS attacks targeting content providers in IP-based and content-centric networks, and proposed a queuing theory based model for DoS attacks modeling. This model considers the caching period of content objects as well as queuing delay at repositories. The authors concluded that DoS attacks in CCN (also applies to NDN) have limited effectiveness in comparison to DoS attacks on IP networks due to satisfaction on interests at intermediate routers. Due to this phenomenon, interest flooding can be localized significantly by increasing routers cache sizes and the timeout period of content in caches.

Despite the correctness of the authors' models, the authors use several unrealistic assumptions. The authors assumed that an attacker only requests content objects that are available at the content provider(s) and may be cached. However, this is not a complete attack scenario; an attacker can request either non-existent content or dynamically-generated content (which may be unpopular and hence useless when cached). Also, the analysis provided does not account for cache replacement policies, which would affect the content caching period. Furthermore, intermediate routers would be more vulnerable targets to DoS than content providers. However, the impact of DoS on routers was not discussed.

Virgilio *et al.* [28] analyzed the security of the existing PIT architectures under DDoS attack. The authors compared three proposed PIT architectures: (1) SimplePIT, which stores the entire URL, (2) HashPIT, where only a hash of the URL is stored, and (3) DiPIT (distributed PIT), where each interface uses a Bloom filter to determine which content objects should be forwarded. The authors concluded that all three proposed PIT architectures are vulnerable to DDoS attack, and they all perform the same under normal traffic conditions. While SimplePIT and HashPIT suffer from memory growth in the face of DoS, DiPIT does not consume extra memory. The Bloom filter's inherent false positive rate has the potential to cause data to be forwarded unnecessarily, and therefore waste bandwidth. Although this paper showed the effects of DDoS on different PIT architectures through simulation, the authors did not propose any viable solution.

Wang *et al.* [29] proposed a mechanism which copes with interest flooding by decoupling malicious interests from the PIT. The mechanism requires that each router monitors the number of expired interests for each name-prefix, then adds a prefix to the malicious list (m-list) if this count exceeds a chosen threshold. To prevent legitimate name-prefixes from staying in the m-list, each m-list entry is assigned an expiry time, after which the prefix is removed from the m-list. However, an m-list entry's expiry timer is reset if a new interest arrives for the same prefix.

The authors overcome the extra load on the PIT table size by putting information in the interest. Although this helps routers keep the sizes of their PITs manageable, they will still be responsible for forwarding the malicious interests; thus network congestion and starvation of legitimate clients are still possible. This mechanism also puts additional processing burden on the routers and increases packet overhead.

Wang *et al.* [30] modeled the interest flooding attack in NDN by considering factors, such as routers' PIT sizes, round trip times, PIT entries' TTLs, content popularity distribution, and both malicious and legitimate interest rates. The authors derived a DoS probability distribution, which evaluates the probability that a legitimate interest will be dropped due to starvation. Simulation results confirmed the validity of the model. The authors suggested that the effectiveness of DoS could be reduced by using bigger PITs, bigger content stores, and shorter TTLs for PIT entries. Nonetheless, these suggestions do not actually address the problem: an attacker could easily increase its request rate proportionally.

b) Approaches that Require Client's Proof-of-Work: Proof-of-work approaches, reduce the request rate from clients (because of the delay in obtaining the proof) and serve as a barrier which only serious clients will overcome to use the network. In the ICN literature, there has been one such work. Li and Bi [31] proposed a DoS countermeasure for dynamic content requests using proof-of-work. As opposed to static content, which is signed once when it is generated, a dynamic content object is generated and signed upon interest arrival. A

TABLE I: Classification of DoS/DDoS Mitigation Approaches and Their Salient Features

Mechanism	Target	Content Type	Mitigation Approach	Router's Functionality	Scope
Rate Limiting					
Afanasayev *et al.* [21]	Router	Non-Existent	Rate Limiting & Per-face Fairness Per-face Statistic & Priority	PIT Extension Storing Statistics	Individual Routers Router Collaboration
Gasti *et al.* [22]	Provider Router	Dynamic Existing & Non-Existent	Rate Limiting & Per-face Statistics	Storing Statistics	Individual Routers
Compagno *et al.* [23]	Router	Non-Existent	Rate Limiting & Per-face Statistics	Storing Statistics	Router Collaboration
Dai *et al.* [24]	Router	Non-Existent	Rate Limiting & PIT Size Monitoring	Not Applicable	Router Collaboration
Statistical Modeling					
Wang *et al.* [25]	Router	Non-Existent	Fuzzy Logic-based Detection	Storing Statistics	Router Collaboration
Nguyen *et al.* [26]	Router	Non-Existent	Statistical Hypotheses Testing Theory	Storing Statistics	Individual Routers
Other Countermeasures					
Wang *et al.* [27]	Provider	Existing	Caching Period Increase	Not Applicable	Individual Routers
Wang *et al.* [29]	Router	Non-Existent	Decoupling Malicious Interest from PIT	Additional Queue	Individual Routers
Wang *et al.* [30]	Router	Existing	Bigger PIT and Cache	Not Applicable	Individual Routers
Li *et al.* [31]	Provider	Dynamic	Client's Proof-of-Work per Interest	Not Applicable	Not Applicable

high rate of dynamic content requests can thus overload the content provider with signature computation, causing DoS. To deter potential attackers the authors proposed a proof-of-work mechanism where the client requests a meta-puzzle from the content provider. Upon receiving the meta-puzzle, the client generates the actual puzzle and solves it (similarly to how blocks are mined in Bitcoin). The puzzle solution and the current timestamp form a part of the interest, which is verified by the provider.

*4) **Summary and Future Directions in DoS Mitigation**:* In Table I, we summarize all the proposed DoS mitigation mechanisms in terms of the entity implementing the mechanism, whether the attack model involves existent, dynamic, or non-existent content requests, the nature of the mitigation approach, the extra functionality needed in the routers, and the level of collaboration required between routers. DoS attacks, in general, either target the routers [21], [23], [24], [26], [29], [30] and/or the content providers [22], [27], [31]. An attacker tries to exhaust either the routers' PITs or content providers' resources by requesting dynamic or non-existent content with a high rate, which causes unbounded service delays for legitimate clients.

The majority of the proposed solutions [21]–[24], especially against the interest flooding based DoS attacks, are variants of a rate limiting mechanism on the suspicious interfaces or name prefixes. The major drawback of the rate limiting based solutions is that they may penalize legitimate clients also. No scheme performs per-flow based rate-limiting, which has the highest fairness. The closest is the approach by Gasti *et al.* [22] where prefix based rate-limiting was proposed. There is need for more fine-grained rate-limiting to better distinguish malicious from benign requests.

Other proposed mechanisms including per-interest client's proof-of-work [31], fuzzy logic-based detection [30], statistical hypotheses testing theory [26], and increasing the caching time [27] have also been proposed to solve the problem. However, these mechanisms either require storage of per content statistics at the routers or are not computationally scalable, especially in the real time. A better mechanism may be one that removes the suspicious requests from the PIT [29], similar to the publish-subscribe Bloom filter based self-routing [9], [10]. This mechanism can be augmented by adopting a self-routing approach for the suspicious interests and using the available stateful routing for the legitimate interests.

Another potential direction is employing a software-defined networking (SDN) approach in which a network controller with an overall aggregated view of the network detects and mitigates the DoS attack in its early stages. It can be achieved by the collaboration of routers at different levels of the network hierarchy, specifically for filtering the communication flows that share malicious name prefixes. Exploiting a more sophisticated interest aggregation method, which aggregates the malicious interests with same prefix (regardless of their suffixes) into one PIT entry, can also slow down the PIT exhaustion. We also believe some of the current IP-based detection and defense mechanisms [81] might be relevant for ICN DoS mitigation. This is a significant area of interest.

An attacker can orchestrate a DoS attack in publish/subscribe networks by manipulating the z-filter in a content packet. This causes each intermediate router to forward the packet to all of its interfaces, creating congestion in the network. However, DoS attack in publish/subscribe networks has not received much attention from the community, except the work proposed by Alzahrani *et al.* [46], [47]. We believe that DoS in publish/subscribe networks is a legitimate security concern, which requires more in depth analysis and solutions.

All the proposed mechanisms try to address interest flooding in CCN and NDN architectures. However, the rate limiting and proof of work approaches can be applied to other architectures, where the attacker targets the intermediate entities such as DONA's resolution handler and NetInf's name resolution server.

B. Content Poisoning Attack

The objective of the *content poisoning attack* is to fill routers' caches with invalid content. To mount this attack, an attacker must control one or more intermediate routers to be able to inject its own content into the network. The injected content has a valid name corresponding to an interest, but a fake payload or an invalid signature. This attack is applicable to all ICN architectures, however, it is less effective in architectures using self-certifying names. With self-certifying names the digest of the packet's content is the name of the packet. Thus it is easier to verify the correctness of a content chunk by comparing the hash of the chunk against the digest and drop packets whose hash does not match.

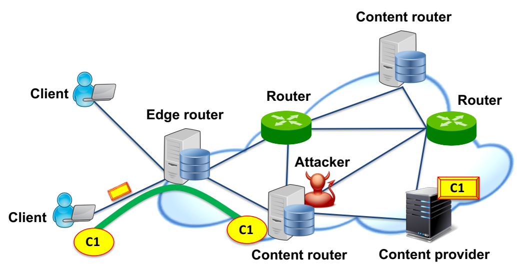

Fig. 5: Content poisoning attack scenario.

We illustrate the poisoning attack in Fig. 5. The attacker is one of the routers on the path between the client and provide returning an invalid content (oval C1) instead of the genuine content (double-border rectangle C1) corresponding to the requested name. This attack can have potentially devastating consequences: unless the content are validated an attacker can fill the network with poisoned content objects, while useful content find no place in the caches.

Fig. 6 illustrates our categorization of content poisoning countermeasures. The first category, *collaborative signature verification*, refers to those mechanisms in which routers co-operate with each other to verify the content signature. The *consumer dependent* category includes those approaches that either rely on using additional fields in request and data packets or clients' feedback. We start with the first category.

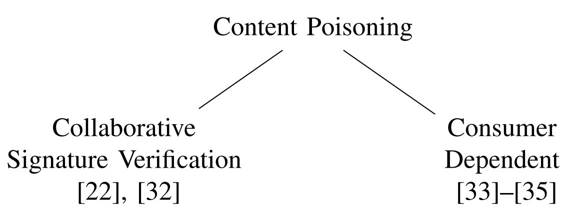

Fig. 6: Content poisoning countermeasure sub-classes and the state-of-the-art.

*1) **Collaborative Signature Verification Countermeasures**:* This category refers to the approaches that propose router verification of signatures of packets they forward. To distribute and reduce the load of signature verification, the routers flag the verified chunks to signal their peers that the packet has been validated, and/or verify the signature of the chunks upon cache hit (only verify popular content).

Gasti *et al.* [22] were the first to discuss the content/cache poisoning attacks. As their first countermeasure, the authors suggested the use of a "self-certifying interest/data packet" (SCID) to help routers validate received content chunks. Before sending an interest, a client is required to obtain the desired chunk's hash, name, and signature from the content provider. This information is attached to the interest. On obtaining a content chunk, a router can check its validity by comparing its hash to the hash from the interest information it has. This method is less computationally intensive than traditional RSA signature verification, however it requires the client to obtain the hashes for each data chunk/packet beforehand and for the routers to store them until verification. This increases content retrieval latency and router storage overhead, thus limiting scalability.

As an improvement, the authors proposed cached content signature verification by routers. In the basic version, each router randomly selects and verifies content chunks, dropping those whose signatures cannot be validated. To prevent redundant verification, routers collaboratively select a range of content chunks to verify. The scope of this collaboration can vary from a neighborhood to an organization. To reduce collaboration overhead, the authors also suggested client feedback based decision-making in which a client may inform its edge router about each content chunk's validity. However, this type of feedback can also be used by malicious clients to mislead routers by reporting legitimate content objects as fake, or vice-versa.

The mechanism proposed by Kim *et al.* [32] was inspired by check before storing (CBS) [82], which probabilistically verifies content items, only storing validated content items in the cache. The authors measured that generally around 10% of the cached contents are requested again before their expiration from their caches. Hence, they divided the cache into serving content, which will be requested while they are cached, and by-passing content, which will be dropped from the cache before subsequent interests.

The authors used a segmented LRU policy for cache replacement: a content is initially put in the by-passing content segment of the cache. The proposed countermeasure only verifies the signature of a serving content, that is a content that has a cache hit. At that point the content's signature is verified and it is moved to the serving content cache segment. To avoid multiple verifications of a chunk, the verified chunk is marked in the serving content cache segment.

The authors simulations showed that the approach resulted in a reduction in the number of poisonous content cached; however, the scheme has some drawbacks. Any chunk that is requested twice still needs to be verified, thus adding to the latency and computation. An attacker can enforce verification of every fake content, by requesting it twice; at scale this could lead to a DoS/DDoS attack. The authors show that with an increase in the serving content cache segment proportion the overall content hit rate goes down. But they do not mention if this reduction in hit-rate is for fake content or for usable serving content; this could have a significant bearing on system efficiency.

*2) **Consumer Dependent Countermeasures**:* In the consumer dependent countermeasures, the clients either give feedback on the legitimacy of the received content or include the providers' public keys in their request packets to enable

TABLE II: Content Poisoning Countermeasures are Classified to Collaborative Verification and Consumer Dependent Classes

Mechanism	Mitigation Approach	Overhead
Collaborative Signature Verification		
Gasti *et al.* [22]	Self-Certifying Interest & Collaborative Signature Verification	Hash Value Comparison & Random Signature Verification
Kim *et al.* [32]	Collaborative Signature Verification of Serving Content	Signature Verification on Cache Hit
Consumer Dependent		
Ghali *et al.* [33]	Client Feedback, Content Ranking	Content Ranking Calculation
Ghali *et al.* [34], [35]	Interest-Key Binding & Adding the Provider's Public key to the Content	PPKD Comparison & Signature Verification

verification. Ghali *et al.* [33] proposed a content poisoning mitigation mechanism while introducing an updated definition for fake content. The authors defined a fake content as one with a valid signature using the wrong key, or with a malformed signature field. The authors discussed the applicability of existing solutions such as signature verification by intermediate routers, which is infeasible at line speed. On the other hand, although self-certifying names are more efficient as a countermeasure, issues such as efficient content hash retrieval and handling of dynamic content objects need solutions. Hence, the authors proposed a ranking mechanism for cached content using exclusion-based feedback.

Exclusion is a selector feature in the CCN and NDN architectures [83], which allows a client to exclude certain data (either by hash or name suffix) from matching its interest, effectively overriding a match on the requested name's prefix. Clients can use this feature to avoid receiving data objects that are known to be unwanted, corrupted, or forged. In the proposed approaches, a detector function ranks content based on three factors: number of exclusions, exclusion time, and exclusion-interface ratio. The exclusion time defines the recency of a particular data name exclusion. A content goes down in rank if it has more exclusions, a recent exclusion, or if the router receives exclusion feedback for it from multiple clients on different interfaces. To overcome poisoning, if a router has multiple cached contents with names that match that requested in the interest, then the router returns the highest ranked content.

The drawbacks of this approach are: it is highly dependent on client feedback; non-cooperative and/or malicious clients can undermine its effectiveness; storage of multiple copies of same content undermines cache efficiency. Furthermore, the exclusion feature is not present in all ICN architectures.

Ghali *et al.* [34], [35] noted that content poisoning mitigation is contingent on network-layer trust management. According to them, cache poisoning attack in ICN is due to interest ambiguity and lack of a trust model. The former arises from the interest packet structure, which considers the content name as the only compulsory field, while neglecting two other fields, the content digest and the publisher public key digest (PPKD). The latter refers to the lack of a unified trust model at the network layer.

As a solution, the authors suggested to clarify interest ambiguity by adding a binding between content name and the provider's public key, an Interest-Key Binding (IKB), to the interest packet. The only modification at the content provider is the addition of the provider's public key to the content's KeyLocator field. An intermediate router, upon receiving a content, matches the hash of the public key present in the KeyLocator field with the interest's PPKD (available in the PIT). The content will be forwarded if these match, and will be discarded otherwise.

The client-side complexity of this approach is in obtaining the provider's public key in advance. In order to bootstrap a trust model, the authors proposed three approaches: a pre-installed public key in the client's software application, a global key name service similar to DNS, and a global search-based service such as Google. To reduce core routers' workload, the authors proposed that edge routers perform the IKB check for all content packets, while core routers randomly verify a subset of content packets. Nevertheless, this mechanism does not scale. Signature verification, which is a public key infrastructure (PKI) based verification, is slow and cannot be performed at line speed, even if only some randomly chosen routers or only edge routers perform the verification. Some other weaknesses of the mechanisms proposed by the authors include the assumption that the verifying router is trusted–perhaps the router is malicious, then it can verify an incorrect IKB to be correct [22], [33]–[35]. Further, the schemes lacked detailed analysis of scalability and overhead.

*3) **Summary and Future Directions in Content Poisoning Mitigation**:* Table II summarizes the basic techniques used in the proposed countermeasures and their overheads. In this attack, the attacker's goal is to fill the routers' caches with fake contents, that are either content with valid names and invalid payloads or content with invalid signatures. All of the proposed mechanisms require the intermediate routers to verify the data packets' signatures [22], [32], compare the content hash in interest and data packets [22], [34], [35], or to rank the contents based on the clients' feedback [33]. Signature verification approaches suffer from delays, which undermine scalability. The client feedback based content ranking approach can be undermined by malicious clients.

We believe that the hash verification based approach is the more promising approach on account of low amortized cost to intermediate routers. More study need to be conducted to identify a suitable cryptographic hash function. Another approach is to trace the fake content back to its origin by leveraging the history of each interface on the route. After successfully detection of the attack origin, a mitigation mechanism can be orchestrated. For instance, a router may prevent caching the content chunks that arrive from a suspicious interface or have the same name prefixes as the fake content. We believe that there is still need for more efficient and scalable mitigation approaches.

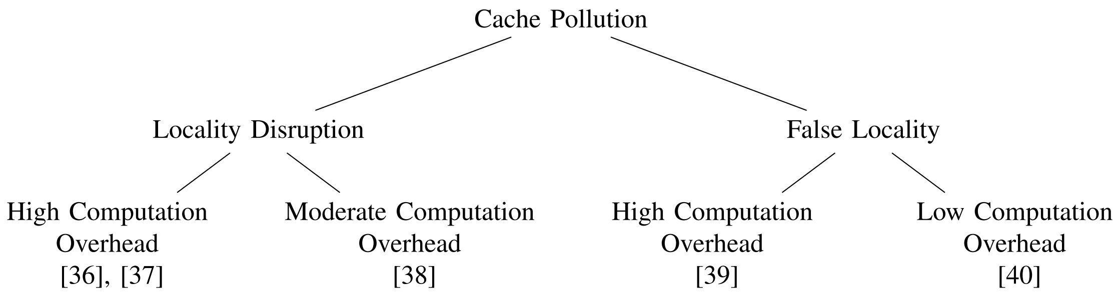

Fig. 7: State-of-the-art in cache pollution countermeasures.

C. Cache Pollution Attack

Caching in ICN is effective, especially if the universe of on the Internet follows a popularity distribution (e.g., Zipf distribution), where a small number of popular contents are requested frequently, while the rest of the contents are requested sparingly. The popular (frequently requested) contents can be caches in the network, thus reducing request latency and network load. However, an attacker can undermine this popularity based caching by skewing content popularity by requesting less popular content more frequently. This is the *cache pollution attack*.

In this subsection, we explore two classes of cache pollution attacks: *locality disruption* and *false locality*. In the locality disruption attack, an attacker continuously requests new, unpopular contents to disrupt cache locality by churning the cache. In the false locality attack, on the other hand, the attacker's aim is to change the popularity distribution of the local cache to favor a set of unpopular contents by repeatedly requesting the unpopular contents set. In principle, this attack is feasible in all ICN architectures. However, in publish/subscribe architectures (e.g., PSIRP and PURSUIT) the attack may have minimal impact. The one-time subscription mechanism used in publish/subscribe architectures means a subscriber cannot artificially increase a content's popularity by requesting it multiple times.

Fig. 7 illustrates the cache pollution attacks categorization: locality disruption and false locality. The attack countermeasures are further subcategorized according to their computation overhead at the intermediate routers. We note that the approach proposed by Karami *et al.* [39] addresses both locality disruption and false locality threats.

1) ***Locality Disruption Mitigation Approaches****:* In the proposed approaches to mitigate locality disruption, the routers either cache the content with certain popularity (attack prevention) or have to periodically evaluate the popularity of their cached content (attack detection). We subcategorized these prevention and mitigation mechanisms based on their computation overhead on the routers into high and moderate subcategories.

a) Approaches with High Computation Overhead: Several proposed locality disruption mitigation approaches require complex and iterative procedures per content caching decision at intermediate routers, thus incurring high computation overhead. For instance, Park *et al.* [36] proposed a cache pollution detection scheme based on randomness check. The iterative scheme takes advantage of matrix ranking and sequential analysis for detecting a low-rate pollution attack: an attacker requesting chunks at a low rate to bypass any rate filters. The detection scheme starts with the routers mapping their cached content onto an $n \times n$ binary matrix M, where $n \simeq [\sqrt{S_c}]$ and S_c is the average number of cached contents. The authors employ two cryptographic hash functions for mapping a content name to location in the matrix and evaluate its rank M. The ranking process is iterated k times, and the attack alarm is triggered if the matrix-rank reaches a pre-defined threshold. Due to its focus on low-rate attacks the scheme does not consider popular contents, which are removed from consideration.

The authors showed the effectiveness of their scheme in detecting low-rate locality-disruption attacks. However, this scheme is not applicable to the harder to detect false locality attack. Furthermore, the proposed approach is computationally heavy for the caching routers.

Xie *et al.* [37] proposed *CacheShield*, a mechanism providing robustness against the locality disruption attack. It is composed of two main components: a probabilistic shielding function, and a vector of content names and their corresponding request frequencies. When a router receives a request for a content chunk, if the chunk is in its CS, it replies with the content. Otherwise, the router forwards the interest towards the provider. When a chunk arrives at the router, the shielding function defined as, $1/(1+e^{\frac{p-t}{q}})$, where p and q are pre-defined system-wide constants and t denotes the t^{th} request for the given chunk, is used to calculate the probability of placing the content in the CS.

If the chunk is not placed in the CS, then the router either adds the chunk's name with a frequency of one in the vector of content names, if it does not exist; if the name exists, then the frequency is incremented by one. A chunk is placed in the CS when the request frequency of the exceeds a pre-defined threshold. This approach suffers from the fact that the shield function's parameters p and q are constants and can be easily deduced (if not known), and hence an attacker can easily calculate the value of t. Then the attacker has to just ensure that it requests the unpopular contents more than t times. Additionally, the portion of the CS used to store the name vector adds to the storage overhead.

TABLE III: Cache Pollution Countermeasures Classified to Locality Disruption and False Locality Classes

Mechanism	Detection & Mitigation Approaches	Attack Type	Router's Overhead	
			Storage	Computation
Locality Disruption				
Park *et al.* [36]	Cached Content Matrix Ranking	Low-rate Locality Disruption	Low	High
Xie *et al.* [37]	Probabilistically Caching Popular Content	Locality Disruption	Moderate	High
Conti *et al.* [38]	Random Content Sampling for Attack Threshold Detection	Locality Disruption	Low	Moderate
False Locality				
Karami *et al.* [39]	Adoptive Neuro-Fuzzy Inference System Replacement Policy	Locality Disruption & False Locality	Moderate	High
Mauri *et al.* [40]	Honeypot Installation & Hidden Monitoring	False Locality (by Content Provider)	Moderate	Low

b) Approaches with Moderate Computation Overhead: There are other proposed approaches that use only a subset of the content at a router to perform attack detection, hence do not suffer from high overhead. For instance, to overcome the shortcomings of CacheShield, Conti *et al.* [38] proposed a machine-learning approach. They evaluated the impact of cache pollution attacks on different cache replacement policies and network topologies. They proposed a detection algorithm, which operates as a sub-routine of the caching policy. The algorithm is composed of a learning step and an attack-testing step. It starts by checking the membership of an arrived content in a sample set chosen from the universe of contents. If the content belongs to the sample set, the learning step will be triggered with the goal of identifying an attack threshold (defined as τ) for evaluating the contents.

The value of τ is used by the attack test sub-routine in the testing step. The attack test sub-routine compares the calculated τ with another value δ_m, which is a function with parameters, such as content request frequency and the size of the measurement interval, of all contents in the sample set. If δ_m is greater than τ, then the mechanism detects an attack. The drawback of this approach is that it only detects the attack, but does not identify the attack interests, or content chunks. Further, the assumption that the adversary's content requests can only follow a uniform distribution is simplistic and may not reflect the reality.

*2) **False Locality Mitigation Approaches**:* The false locality attack can be orchestrated by malicious consumers and/or producers. A malicious consumers' goal is to alter the content popularity in the local caches, while malicious producers' intent is to store its content in the routers' caches. As with the cache pollution attack, we subcategorized the proposed countermeasures into high and low computational overhead.

a) Approach with High Computation Overhead: Karami *et al.* [39] proposed an Adaptive Neuro-Fuzzy Inference System (ANFIS) based cache replacement policy resilient to cache pollution. The policy has three stages: input-output data pattern extraction, accuracy verification of the constructed ANFIS structure, and integration of the structure as a cache replacement policy. In the first stage, an ANFIS structure is constructed according to the properties of the cached content. Variables such as a content's time duration in cache, request frequency, and standard deviation of the request frequency, are all fed into a nonlinear system. The system returns a goodness value between 0 and 1 per content (0 indicates false-locality, 0.5 indicates locality-disruption, and 1 indicates a valid content).

The system iteratively evaluates the goodness of the cached contents that have been cached beyond a predefined time period. The system selects the contents with goodness values less than a goodness threshold, ranks them, and applies cache replacement over the content with low goodness values. The authors showed the advantages of their proposed mechanism over CacheShield in terms of hit damage-ratio (proportion of hits that cannot occur due to the attack), percentage of honest consumers receiving valid contents, and communication overhead. However, this mechanism needs to store historical and statistical information for each cached content–a significant memory overhead. Additionally, the iterative computation of statistics undermines scalability.

b) Approaches with Low Computation Overhead: Mauri *et al.* [40] discussed a cache pollution scenario in NDN, where a malicious provider intends to malign the routers' cache to preferentially store its own content for lower latency. The authors assumed that the provider used colluding terminal nodes (bots or zombies) to request its content(s). This results in a disproportionately larger portion of the attacker's content catalog to move down to the network edge, thus improving its delivery latency. The authors proposed a mitigation mechanism for this attack that used a honeypot installed close to potential zombies, which monitors and reports the malicious interests to the upstream routers. A router gathers these interests into a blacklist; the interests in this blacklist are routed to the provider using the standard NDN routing protocol, not the CS or nearest replica. The proposed solution incurs low computation overhead on the routers, however, it requires additional infrastructure.

*3) **Summary and Future Directions in Cache Pollution Mitigation**:* In Table III, we summarize the proposed cache pollution solutions based on their detection and mitigation approaches, and the nature of the attack. We also present the storage and computation overheads for each solution at the routers. Cache pollution is divided into false locality and locality disruption attacks. The objective of these attacks is to degrade cache effectiveness and increase the content retrieval latency. Some of the proposed approaches [36], [37], [39] incur high computation cost at the intermediate routers, which undermines their scalability. Other proposed mechanisms either only detect the cache pollution attack [38] or address the less severe malicious provider attack scenario [40]. All the proposed

TABLE IV: Secure Naming Approaches are Classified According to their Underlying Cryptographic Schemes

Mechanism	Crypto	Provenance	Drawbacks
RSA Crypto			
Wong *et al.* [41]	RSA	Pub. Key Digest	PKG Requirement for Private key Generation
Dannewitz *et al.* [42]	RSA	Pub. Key Digest	Lack of Evaluation & Scalability Issue
IBC Crypto			
Zhang *et al.* [43]	IBC	IBC Signature	Scalability Issue & Public key Length
Hamdane *et al.* [44]	HIBC	IBC Signature	Signature Verification Overhead

mechanisms except [40] can be applied to ICN architectures that leverage caching.

We believe that the key aspect of a solution is in designing a robust caching mechanism, which not only increases the resiliency of the cache against these attacks, but also improves the overall network latency and users quality of experience. One possible direction is further exploration of collaborative caching. Proposed collaborative caching schemes have aimed at improving cache utilization and reducing latency [84]–[86]. However, the positive impacts of collaborative caching mechanisms on mitigating cache pollution attack have not been explored. With collaborative caching and feedback between the caches, mechanisms can be designed to contain or root out cache pollution attack attempts. For instance, a coalition of collaborative caches can exchange cache states and cached content popularity to reduce caching of unpopular content [87], [88].

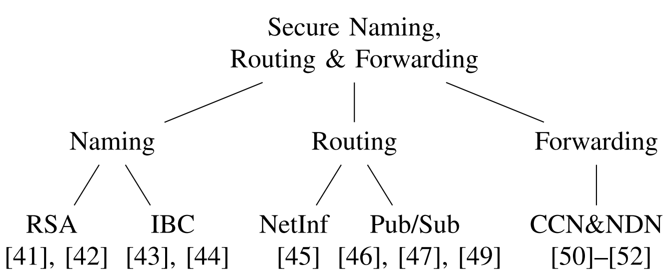

Fig. 8: The state-of-the-art in secure naming, routing, and forwarding.

D. Secure Naming, Routing, and Forwarding

Content naming scheme (name schema) is an integral aspect of ICN. In ICN, a verifiable binding between the content name and its provider can help nullify attacks such as content poisoning. Secure naming is also essential for verifying provenance of a content (an important feature of ICN). Secure routing and forwarding on the other hand are essential aspects of any network architecture. All three architectures we are discussing (NetInf, Publish/Subscribe, and CCN/NDN) have their own nuances in routing and forwarding, each leveraging their core-features. In this subsection, we discuss the proposed security enhancements on these routing and forwarding approaches. Secure routing has been the focus of the NetInf and Pub/Sub approaches while secure forwarding has been the focus in CCN/NDN (NDN in particular).

Fig. 8 categorizes the proposed mechanisms into *secure naming*, *routing*, and *forwarding* categories. The approaches in the secure naming category are sub-categorized, based on their underlying cryptographic schemes, to *RSA-based* and *IBC-based* subcategories. As mentioned, we sub-categorize secure routing and forwarding based on the underlying architectures.

*1) **Secure Naming**:* All the proposed naming schemes can be easily categorized into either those that use RSA cryptography and those that use identity-based cryptography. We follow this categorization.

a) Approaches using RSA: The approaches using RSA either use the provider's public key or its digest to guarantee content provenance. Wong *et al.* [41] proposed a secure naming scheme to establish trust between content providers and clients. The scheme uses a metadata composed of three identifiers: authority identifier (ID), which is generated from the provider's public key; content identifier, which is the cryptographic hash of the content; and algorithmic identifier, which binds the content identifier with a set of the content fragment/chunk identifiers. Based on the URI naming convention, the authority field is mapped to the provider's public key and the resource path field holds the content identifier. The content metadata are disseminated into a set of network nodes that function as part of a domain name system and also store the metadata in a DHT. For content retrieval, a client queries the DNS to resolve the content name into a digital certificate. By extracting the authority identifier from the certificate, the client obtains the metadata that has to be resolved by the DHT. The query to the DHT returns the content and algorithmic ID, which the client uses to request the content. This approach suffers from scalability concerns such as header overheads and the latency due to DNS and DHT queries, which the authors have not discussed.

In a similar vein, Dannewitz *et al.* [42] proposed a naming scheme for NetInf. They proposed an information object (IO) for each content as a tuple composed of the content ID, the content, and a piece of metadata. The content ID follows a self-certifying flat structure containing type, authentication, and label fields. The type field specifies the hashing function used for ID generation. The authentication field is the hash value of the provider's public key; and the label field contains a number of identifier attributes and is unique in the provider's domain. The IO contains the provider's complete public key and its certificate, a signature over the self-certified data, and the hash function used for the signature. This scheme has several weaknesses: the IO field can be a big transmission overhead; the signature verification if it happens per chunk can be expensive, and if it happens after the whole content is downloaded can enable cache poisoning or pollution attacks.

b) Approaches that Employ IBC Cryptographic Scheme: In this subcategory the approaches use a binding between the content name and the corresponding provider's public key. Zhang *et al.* [43] proposed a name-based mechanism for efficient trust management in content-centric networks. This mechanism takes advantage of identity-based cryptography (IBC), in which either the provider's identity or the content name prefix is used as the public key. A trusted private key generator (PKG) entity generates the private key corresponding to the public key. For the content name prefix to be used as the public key a name resolution service is required to register the name prefix (for uniqueness).

Despite its advantages, use of IBC implies that PKI is still needed to secure communication between the PKG and other network entities. Additionally, the use of the content name prefix as the public key is a new approach and needs further investigation. Another significant drawback is the need for a trusted PKG, which is another entity that needs to be added into the system; which undermines usability.

Hamdane *et al.* [44] proposed a hierarchical identity-based cryptographic (HIBC) naming scheme for NDN. This scheme ensures a binding between a content name and its publisher's public key. The identity-based content encryption, decryption, and signature mechanisms follows [43]. Different from the previous work, the authors proposed a hierarchical model in which a root PKG is responsible only for generating private keys for the domain-level PKGs. The domain-level PKGs perform the clients' private key generation. This scheme has the same scalability concerns as the previous scheme on account of the encryption/decryption costs. In fact, the overhead is higher as the size of the public key is longer and grows additively with the depth of the hierarchy.

Table IV summarizes the existing secure naming schemes and presents the type of cryptography used, the mechanism for ensuring provenance, and the nature of the encryption infrastructure. We note that the proposed naming schemes have significant overheads. Reducing these overheads or at least amortizing their cost over the complete set of interests/responses is an open research area.

*2) **Secure Routing**:* We categorize the proposed secure routing schemes, according to their underlying architectures, into secure routing in NetInf and Publish/Subscribe networks.

a) Approaches for Secure Routing in NetInf: Two approaches have been proposed to secure routing in NetInf. Both aim to establish secure communication between public and private domains (Rembarz *et al.* [45]). The first approach, *gateway-centric* approach, uses a gateway to route all communications between the public and private networks. A publisher in the private domain publishes a content to a private name resolver, PNR, which resides in the private domain. The PNR informs a public name resolver (NR) in the public domain, about the published content's identifier along with the gateway's location; instead of the actual publisher's location. A public subscriber resolves the content identifier at the public NR and obtains the gateway address. The subscriber successfully authenticates itself to the gateway for the gateway to resolve the content identifier at the PNR and delivers the content from the publisher to the subscriber.

In the second approach, the publisher in the private domain publishes its private data identifier to a PNR. The PNR creates a mapping between the content identifier *ID* and a generated alternative identifier *ID'* that is sent to the NR. A subscriber, in the public domain, contacts the NR to resolve *ID'* to its location. The authentication happens at the PNR. This mechanism removes the gateway, a single point of failure, in the first approach. However, the PNR's computation and communication overhead for subscribers authentication and authorization (especially when the private network serves large amounts of requests) undermines the scalability of this approach.

b) Approaches for Secure Routing in Publish/Subscribe: The proposed approaches for secure routing in publish/subscribe (pub/sub) networks focus on designing DoS-resistant self-routing mechanisms and key management approaches that prevent malicious publishers from generating fake routes. Alzahrani *et al.* [46], [47] proposed a DoS-resistant self-routing mechanism using Bloom filters. In pub/sub networks, each network link is assigned a unique identifier (LID), which is represented in the form of a Bloom filter. When a network entity requests for a path from the client to the content location (publisher or a cache), an entity called the topology manager (TM), resident in one or more routers, generates a filter (z-filter) that specifies the delivery path from a publisher to the subscriber by OR-ing the Bloom filters (LIDs) of the links on the delivery path. At the intermediate routers, an AND operation between the z-filter (in the packet header) and the routers' LIDs on the path identifies the delivery links.

This mechanism is vulnerable against DoS attack. An attacker can collect enough z-filters and reuse them to overload the frequently used delivery path(s) with bogus traffic. As a remedy, the authors suggested the use of temporal link identifiers that become stale after a pre-defined time period. This temporal, per-flow z-filters was designed to restrict the attacker's impact. The remedy introduces two drawbacks; first, the number of z-filter updates increases with a decrease in the time interval–a trade-off between attack mitigation and computation overhead at the TM. Second, the size of the packet header (includes the z-filter) increases with the number of links in the delivery path. The authors also investigated factors that affect the z-filter's size in [48].

Alzahrani *et al.* [49] proposed a key management protocol for publish-subscribe networks which utilized dynamic link identifiers. Following up on [46], [47] the authors proposed an enhancement that prevents a malicious publisher from generating fake z-filters by enabling the publisher's edge router to verify the TM generated z-filter. Fake z-filters can enable the transmission of a large number of packets aimed at overwhelming unwitting subscribers. The TM shares a symmetric key with the publisher's edge router and uses it to cryptographically hash the corresponding z-filter and it's generation timestamp, and forwards both to the publisher. The publisher adds these information to each packet that it forwards towards the subscriber. The proposed mechanism is vulnerable against the malicious publisher colluding with its edge router. In addition, this mechanism requires stateful routers, which are vulnerable against DoS attacks (similar to CCN/NDN DoS-flooding attack).

Fotiou *et al.* [89] reviewed a clean-slate PSIRP networking architecture and highlighted its security assurances. The architecture employs self-certifying names, each composed of a rendezvous identifier (RID) and a scope identifier (SID). To preserve information security, content transmissions are encrypted and include packet-level authentication (PLA): packet header contains the sender's signature, public key, and certificate. The forwarding mechanism utilizes a z-filter generated by the topology manager to define the information delivery path. As already discussed, z-filters suffer from scalability and false positives. Apart from that, the use of per-packet cryptographic signatures in PLA makes line-speed operations difficult.

*3) **Secure Forwarding**:* The secure forwarding category includes mechanisms that either secure the forwarding plane or create a secure namespace mapping, which allows interest forwarding for name prefixes not in the routers FIB tables.

Yi *et al.* [50] augmented the NDN forwarding plane to thwart security problems, such as prefix hijacking and PIT overload (cases of authenticated denial of service). In prefix hijacking, an attacker announces the victim's prefix and drops the interest. The authors suggested the use of interest NACKs whenever requests are not satisfied for reasons, such as network congestion, non-existent content, and duplicate content. The interest NACK helps reduce the size of the PIT on account of the NACK removing a PIT entry. Additionally, it mitigates the prefix hijacking vulnerability, by providing extra time for the router to query other faces for a content match. However, this requires each router to store RTT information for each interest– a significant overhead for core routers. Additionally, with the NACK consuming an interest in the PIT, there is no scope for bogus interest aggregation; this could exacerbate interest based DoS attacks.

Ghali *et al.* [51] proposed a secure fragmentation mechanism for content-centric networks. Unlike the chunking procedure already performed by content providers, content fragmentation may happen anywhere in the network–necessary if a chunk larger than a link MTU (maximum transmission unit) must be forwarded. The authors argued for per-hop reassembly of fragments for routing efficiency. However, such reassembly requires a more sophisticated content integrity verification mechanism. Therefore, the authors proposed a method of incremental fragment verification for out-of-order fragment delivery. Simulation results show that retrieving a 32KB content with the proposed fragmentation mechanism is about 2.5 times slower than baseline CCN. Though fragmentation increases the flexibility of the network, it results in significant increase in latency.

Afanasayev *et al.* [52] proposed a secure namespace mapping scheme, which allows interest forwarding for name prefixes that are not in the FIB—useful to handle node mobility. The proposed mechanism is built upon two main concepts: *link object* and *link discovery*. The link object is an association between a name prefix and a set of globally routable prefixes. By creating and signing a link object, the content owner maps its own name prefix to those globally routable prefixes. The authors designed an NDN based DNS service (NDNS), where the mapping between the name prefix and the globally routable prefixes are stored, and the service provides this mapping to a requesting entity.

For link discovery, a client queries the NDNS iteratively for each component of the requested name prefix. If a client sends an interest that a router cannot satisfy using its FIB, that router returns a NACK. After the NACK reaches the client, its local forwarder discovers and validates the link object corresponds to the name prefix. After that, the client embeds the link object in its original interest and forwards it to the network. Although this scheme is a good initial solution to provide mobility it suffers from overheads. When a provider moves, the current routable prefix, which is in the FIB of the routers, will results in interests being routed to the provider's former location until the FIB entries time out; a waste of bandwidth in high traffic scenarios.

Table V summarizes the proposed secure routing and forwarding approaches and presents the architecture, the objective of the proposed mechanism, and solution to that problem. Among the proposed mechanism, the work by Afanasayev *et al.* [52] is the most important as it has addressed the producer mobility; an open challenge in the ICN community.

*4) **Summary and Future Directions in Secure Naming, Routing, and Forwarding**:* The proposed approaches for secure

TABLE V: Secure Routing and Forwarding Approaches are Classified with Regard to the Architectures

Mechanism	Architecture	Objective	Proposed Solution
Secure Routing			
Rembarz *et al.* [45]	NetInf	Secure inter-domain communication	Name Resolution Service & Gateway redirection
Alzahrani *et al.* [46], [47]	Pub/Sub	DoS resistant Bloom Filter-based routing	Employing temporary link identifier for z-Filter Generation
Alzahrani *et al.* [49]	Pub/Sub	Malicious publisher with fake z-Filter	Publishers edge router validates z-Filters in data packet
Fotiou *et al.* [89]	Pub/Sub	Identity-based Authentication for DoS mitigation	Each router validates signature, routing using z-Filter
Secure Forwarding			
Yi *et al.* [50]	CCN/NDN	Prefix Hijacking & PIT Overload	Employing NACK Packet for Unsatisfied Interest
Ghali *et al.* [51]	CCN/NDN	Secure content fragmentation	Buffering and reassembly of chunks' fragments at each router
Afanasayev *et al.* [52]	CCN/NDN	Secure Namespace Mapping	Associating a Name Prefix to Globally Routable Prefixes

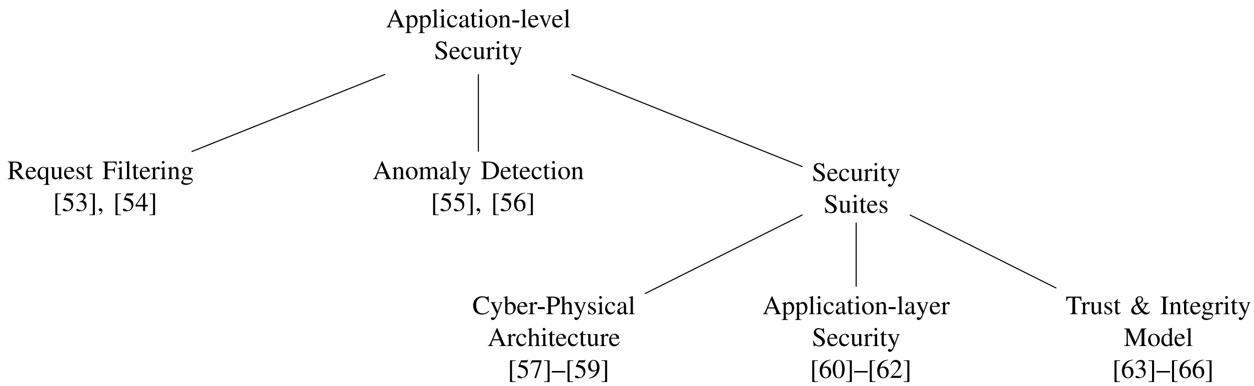

Fig. 9: Application-level security sub-classes and the state-of-the-art.

naming and routing in the ICN architectures are a good first attempts to address the malicious attacks possible. A content naming scheme with a verifiable binding between the content name and its provider is essential to nullify attacks such as content poisoning attack and is integral to ICN. However, in all proposed approaches [41]–[44] this binding comes at the high cost of signature verification (complete verification of binding requires signature verification of each chunk), which would prevent intermediate routers from verifying signature of all arriving packets to maintain line speed. There is still a need for more scalable and computationally efficient approaches. The identity based cryptographic approaches [43], [44] require the client to trust a third party for private key generation; a practice that significantly undermines the applicability of these approaches.

A secure and efficient naming scheme is still an open challenge. Any such scheme should include metadata, such as the content hash and the provider's identity and signature for enhanced security. For instance, a potential secure naming approach can be signature of the manifest (includes chunk names and hashes) by the content provider. This is currently an important area of research with proposals being made to the ICN Research Group, an Internet Research Task Force [90].

On the other hand, secure routing and forwarding (and routing and forwarding in general) do not perform acceptably consumer and/or producer mobility. Even though this has not appeared in the literature, employing Bloom filter based routing (z-filter) in pub/sub networks leads to a potential routing attack. Unless the Bloom filter is authenticated by an intermediate router, an attacker or a malicious router can easily modify the bits in the filters to either overload the network or disrupt content delivery. Developing efficient mechanisms to help routers validate the integrity and authenticity of the z-filters needs more research focus.

E. Application-level Security

We have classified the works in ICN application layer security into three major subtopics: *filtering*, *anomaly detection*, and *security suites*. Fig. 9 illustrates our categorization and the subcategorization within the categories followed by a mention of the corresponding state-of-the-art. The filtering category deals with the identification and removal of unwanted content, such as spam, forged content, and content from untrusted publishers at the application layer. Anomaly detection includes the detection of undesired activities, such as flooding, misbehavior of network elements, and malicious traffic.

We have designated application-specific security measures as security suites, which combine different cryptographic techniques to achieve specific goal(s). We sub-categorize the mechanisms in security suites into it cyber-physical architecture, *application layer security*, and *trust and integrity model*. The cyber-physical architecture subcategory deals with the proposed ICN-based architectures for smart grid, smart home, and Internet of things. The application layer security, reviews the security applications for ICN, such as secure email, covert channel, and information sharing. The trust and integrity model subcategory include the proposed mechanisms that build trust in the network.

1) ***Request Filtering****:* The state-of-the-art in request filtering either utilizes content ranking or exploits providers' information, such as public keys and name prefixes, to block spams and blacklisted content. Fotiou *et al.* [53] proposed an anti-spam mechanism for publish/subscribe networks. It is based on an *inform-ranking* process, with content ranked based on votes from publishers and subscribers. Each publisher serving a content implicitly votes for that content. After the content is published, it is voted on by subscribers. After the votes are collected, they are used to rank the content objects and identify spam objects.

Simulations showed that the mechanism filters spams better than other existing schemes, which only consider the publisher votes for ranking. However, this scheme's reliance on user feedback may counteract its effectiveness. Not only are typical users unlikely to vote on the content, but malicious users can hijack the voting process. Moreover, the voting process itself confers non-negligible communication overhead.

Goergen *et al.* [54] designed a semantic firewall for content-centric networks. Unlike IP firewalls, which filter at flow-level granularity, the proposed firewall can filter content based on provider and/or name. For provider-based filtering, the firewall used provider's public key to identify disallowed providers and filter contents with invalid signatures. For content-name filtering requests with blacklisted keywords in the name are filtered. Both types of filtering can be performed on either interests or the content chunks.

Additionally, the firewall could monitor for abnormal behavior on each of its interfaces and filter abnormal peers (e.g., high request volume or high drop rate). A minimalistic evaluation showed that the firewall's latency increases slowly with an increase in the number of filtering rules. However, latency and scalability in the face of large number of content chunks or large content universe has not been analyzed.

*2) **Anomaly Detection**:* Most proposed anomaly detection mechanisms aim to detect abnormal behaviors by using classification or fuzzy logic algorithms on routers statistical information. Goergen *et al.* [55] proposed a mechanism for CCN to detect attack patterns based on the activities of the FIB, PIT, and CS. To detect abnormal behavior, each node periodically evaluates per-second statistics, such as bytes sent/received, content items received, and interests received, accepted and dropped. The mechanism uses a support vector machine (SVM) to classify a particular time period as either anomalous or benign. The results show the efficacy of this method for attack detection; however, its ability to detect low-rate attacks is questionable. Furthermore, the computation cost of SVM at the network elements may be prohibitive; a software-defined networking based approach may be a good direction to explore.

Karami *et al.* [56] proposed a combined Particle Swarm Optimization (PSO) meta-heuristic, k-means clustering, and a fuzzy detection algorithm for CCN to classify normal/abnormal behaviors. The fuzzy approach is notable for its low false-positive rate; however, at the cost of an increased false-negative rate. An attacker with sufficient resources can produce a large amount of traffic to ensure its malicious packets get through the system without detection.

*3) **Security Suites**:* Here we discuss the several security suites proposed for ICN architectures based on our categorization: cyber-physical architecture, application layer security, and trust and integrity model.

a) Cyber-Physical Architecture: This subcategory includes ICN inspired communication architectures for cyber-physical system, such as the Internet of Things (IoT) and smart grid networks. Burke *et al.* [57] presented a security framework for a CCN-based lighting control system. In the first variation of the protocol, control commands required a three-way handshake and were transmitted in a signed content payload; in the second, the commands were immediately sent as a signed interest. The framework uses an authentication manager to manage the network's PKI, and employs shared symmetric keys for communication. To reduce the burden of key storage on the embedded devices, these symmetric keys can be generated on-demand by a pseudorandom function. These shared symmetric keys can then be used to enforce encryption-based access control.

The authors in [58] employ a similar architecture for secure sensing in IoT. The system uses a trusted authorization manager (AM) to generate the root keys, which are used to sign other keys used. The AM associates a producer with a namespace, which is listed in the producer's certificate. Each sensor is also assigned an access control list, which specifies the permissions of each application with respect to that node. While this scheme is flexible, it suffers from a significant overhead problem—power-constrained devices such as sensing nodes are required to perform asymmetric-key cryptography.

Vieira and Poll [59] proposed a security suite for C-DAX, an information-centric Smart Grid communication architecture. The proposed security suite employs content-based cryptography, in which content topics are used as public keys, and the corresponding secret keys are generated by a security server. For each topic, write-access secrets and read-access secrets must be distributed to each authorized publisher and subscriber, respectively. While the scheme provides sufficient security and flexibility for typical applications, its reliance on a central security server constitutes a single point of failure. In a high-impact critical infrastructure such as the Smart Grid, the failure or compromise of this service could have dire consequences. Also, requiring cyber-physical devices to store two keys for each topic limits scalability.

b) Application layer Security: This subcategory includes secure ICN-based application layer protocols, such as secure email service, covert channel, and information sharing. Saleem *et al.* [60] proposed a distributed secure email service for NetInf, based on asymmetric-key cryptography. Each email message is treated as an independent object. A client (user) is identified by its public key, and no domain name service is required thus providing scalability. However, the subscription-based nature of the service potentially leaves users vulnerable to spam, and no mitigation for this has yet been proposed.

Ambrosin *et al.* [61] identified two different ways of creating an ephemeral covert channel in named-data networking. The sender and receiver require tight time synchronization and agreement on a set of unpopular contents to exploit. To send a "1" covertly, the sender requests an unpopular object during a time slot; to send a "0," no request is sent. In the first variation, the object is assumed to be cached at the edge router if it was requested. The receiver then requests the same content, and measures the retrieval time to differentiate a cache hit from a cache miss, and consequently infers the bit that was sent. This mechanism is accurate when the sender and receiver are collocated behind the same edge router; therefore, its applicability is limited.

Asami *et al.* [62] proposed a moderator-controlled information sharing (MIS) model for ICN, which provides Usenet-like functionality while leveraging identity-based signature scheme. Several message groups are defined, each of which is assigned a moderator. To publish a message in a group, the publisher signs with its secret key then sends it to the group moderator. The moderator can then sign the message and relay it to the group's subscribers, or reject the message and drop it. To verify a signature, the subscriber only needs to know the identities of the publisher and moderator. This is an example of implementation of a secure legacy application in ICN.

TABLE VI: Categorization of Application Security approaches

Mechanism	Application	Approach
Filtering		
Fotiou *et al.* [53]	Anti-spam mechanism	Information ranking based on publishers and subscribers votes
Goergen *et al.* [54]	Semantic firewall	Filtering by content name, provider's public key, and anomaly detection
Anomaly Detection		
Goergen *et al.* [55]	Traffic anomaly detection at routers	Statistical data analyses and SVM classification
Karami *et al.* [56]	Anomaly detection mechanism	Fuzzy detection algorithm and traffic clustering
Security Suites		
Cyber-Physical Architecture		
Burke *et al.* [57]	Lighting control system	Submitting commands as signed content or signed interest
Burke *et al.* [58]	Secure sensing in IoT	Assigning a sensor an ACL for content publishing
Vieira *et al.* [59]	Security suite for Smart Grid	Content-based cryptography and access level distribution via security server
Application-Layer Security		
Saleem *et al.* [60]	Secure email service	Asymmetric crypto with emails as independent objects
Ambrosin *et al.* [61]	Ephemeral covert channel	Time difference analysis between cache hit and cache miss
Asami *et al.* [62]	Moderator-controlled information sharing	Publisher signature followed by moderator signature for message publications
Trust and Integrity Model		
Wong *et al.* [63]	Content integrity by security plane	Content signature and publisher authentication to security plane
Seedorf *et al.* [64], [65]	Self-certifying names and RWI binding	Employing a Web-of-Trust
Yu *et al.* [66]	Trusted data publication/consumption	Schematized chain-of-trust

c) Trust and Integrity Model: This subcategory focuses on directions, such as dedicated security plane, self-certifying names to real-world identities binding, and trust schema creation. Wong *et al.* [63] proposed a separate security plane for publish/subscribe networks for assuring content integrity. The security plane takes over the distribution of authentication materials and associated content metadata from the data plane. The materials distributed by the security plane would include the content name and ID, the Merkle tree root, the publisher's public key, and the publisher's signature. To prevent the insertion of malicious metadata, publishers identify themselves to the security plane and submit to a challenge-response authentication. We believe that while it is convenient for data to be separated from its authentication materials, a separate control plane is ultimately unnecessary. The integrity assurances can be provided by implementing simple content-signing schemes, such as the manifest-based content authentication supported by CCN or NDN [1].

Seedorf *et al.* [64], [65] proposed a mechanism for binding self-certifying names and real world identities (RWIs) using a Web-of-Trust (WoT). A WoT is a directional graph, in which nodes (users) are identified by an RWI-public key digest pair. Edges represent trust relationships: an edge from a node u to a node v indicates that v's certificate has been signed by u. User u trusts another user v if there exists a path starting at u, reaching v in the WoT. Although this mechanisms is very useful in infrastructure-less networks (e.g., disaster response networks) it may suffer from inefficiencies based on the size of the WoT graph, graph updates in the event of network segmentation, and inaccuracies based on the basic notion of a trust chain.

Yu *et al.* [66] presented a schematized trust model for named-data networks to automate data authentication, signing, and access procedures for clients and providers. The proposed model is composed of two components: a set of trust rules, and trust anchors. Trust rules define associations between data names and the corresponding keys that are used to sign them. The authors define a chain of trust, which is discovered by recursively evaluating trust rules, starting from the *KeyLocator* field in the content and ending at a trusted anchor. Anchors are envisioned to serve as trusted entities that help bootstrap the key discovery process. For data authentication, the client uses the public key in the KeyLocator of the packet and according to the trust schema, recursively retrieves public keys to reach a trust anchor to verify the content.

The iterative discovery and key verification step may become inefficient for mobile or IoT devices that are power constrained. Further the trust rules may become complex quickly within a few levels, thus requiring a mechanism for automatic creation of the trust chain in an application. The scheme will have limited applicability until then.

*4) **Summary and Future Directions in Application Security**:* Table VI summarizes the proposed application-level mechanisms. The table contains the proposed approaches reference, the corresponding application, and the approaches' information. We note that several interesting applications have been considered in the ICN domain.

Different ICN security applications and application-level security mechanisms, such as content filtering, anomaly detection, and covert channel have been proposed in the literature. Mechanisms proposed in [53]–[56] attempt to detect abnormal traffic at the intermediate routers, spam contents based on the subscribers' and publishers' votes, or performed content filtering through the firewall. In [57]–[59], the authors proposed ICN inspired architectures for lighting control systems, Internet of things, and the smart grid. In [66], Yu *et al.* proposed a chain-of-trust based schema for content publishers and consumers to use to share content. The authors in [63] suggested the separation of data and security planes for better content integrity assurance. Other proposed applications include ephemeral covert channel communication [61], secure email service [60], and moderator-controlled information sharing [62].

We have not found an application that incorporates all the security functionalities available in ICNs (any architecture) nor did we find a comprehensive application-level security suite (again for any architecture). That should be one of the interests of future researchers in this domain.

3. Privacy in ICN

In this section, we explore privacy risks in ICNs and the proposed mitigation mechanisms. Privacy attacks in ICN may target the routers, cached contents, content names, content signatures, as well as client privacy. These privacy concerns are applicable to all architectures. Additionally, a few attacks are possible due to the inherent design choices of specific architectures; we discuss them separately. We will highlight the vulnerable design choices and discuss their advantages and disadvantages.

Fig. 10 presents our categorization of privacy attacks in ICNs, along with the proposed mitigation mechanisms. We categorize privacy attacks into *timing attack*, *communication monitoring attack*, *censorship and anonymity attack*, *protocol attack*, and *naming-signature privacy*. In timing and communication monitoring attack (Subsections 3.A, 3.B), the attackers probe the cached content of a router over time to identify content popularity in the cache or requesters content access behavior. In Subsection 3.C, we discuss the proposed approaches for anonymous communication. The protocol attack subsection (Subsection 3.D), reviews the vulnerable design features of an architecture, such as longest prefix matching and the scope field. The name of a content in ICN and its signature by design ties the content to the producer's identity, which raises concerns of producer (publisher) privacy. In Subsection 3.E, we discuss the privacy concerns from this exposure and review the literature on publishers privacy.

Before discussing the state of the art based on these categories, we mention one work that is general, and hence goes across several of the above categories, hence merits a standalone definition. Fotiou *et al.* reviewed the proposed ICN architectures and discussed the privacy requirements and design choices for secure content naming, advertisement, lookup, and forwarding in [109]. The authors classified each privacy threat as either a monitoring, decisional interference, or invasion attack. The decisional interference attack either prevents a consumer from accessing certain content, prevents the content advertisement and forwarding of a specific provider, or allows content filtering based on content name. In the invasion attack, an attacker tries to acquire sensitive information from the target. The authors also analyzed the identified threats and ranked them according to the DREAD model [110], and briefly reviewed ongoing research on privacy concerns in information-centric networking. Now, we discuss the categories.

A. Timing Attack

Timing attack has been explored in a large body of literature [6], [91]–[94]. In a timing attack, an attacker probes content objects which it believes are cached at a shared router. The attacker leverages precise time measurements to distinguish cache hits and cache misses, and thereby can identify which contents are cached. A cache hit implies that the content had been requested by another client in the neighborhood, while a cache miss indicates that the content has not been requested (or has been evicted from the cache). An informed attacker can also ascertain whether the request is served by the provider or by a router somewhere along the path to the provider. As illustrated in Fig. 11, a shorter latency in retrieving content **C1** in comparison to content **C2** reveals the availability of **C1** in the shared edge router's cache.

We note that this attack, although feasible in all architectures employing caching, is less effective in the pub/sub architectures. In pub/sub (specifically PSIRP/PURSUIT), when a node subscribes to a publisher's content, the latencies of the initial packet deliveries (already created and potentially cached packets) can be used to see whether the packet came from a nearby or farther cache publisher. The timing of subsequent (newly generated) packets do not reflect caching latencies as they are disseminated by the publisher and multicast into the network, and may not even be delivered from a cache.

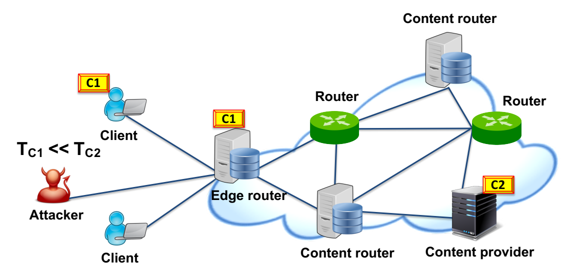

Fig. 11: Timing attack scenario.

*1) **Timing Attack Mitigation Approaches**:* Acs *et al.* [91] investigated cache privacy in CCN/NDN networks in the presence of timing and cache probing attackers. They confirmed the effectiveness of these attacks in different network topologies, and demonstrated attack feasibility even when the attacker and the victim are three hops away from a shared router (success rate of 59%). They discussed two traffic classes: interactive traffic and content distribution traffic. For interactive content, the authors proposed the addition of a random number to the content name; the number is mutually agreed upon by the requester and the content provider. This prevents the attacker from successfully probing the cache for this content if the precise content name matching approach is employed.

However, this approach does undermine caching–cached content can no longer be reduced. As an alternative solution, the authors suggested that the requester and producer mark privacy-sensitive interests and content as private. The intermediate routers do not cache these marked content, thus preventing privacy leaks. The authors also suggested the emulation of a cache miss at a router, with the router applying a random delay before satisfying a content chunk request. But, a delay undermines user's quality of experience (QoE).

The authors reduced the impact on QoE by using a popularity threshold. The premise of the model is that the privacy-sensitive contents are usually unpopular, and that increased popularity generally results in reduction of the privacy need. With this

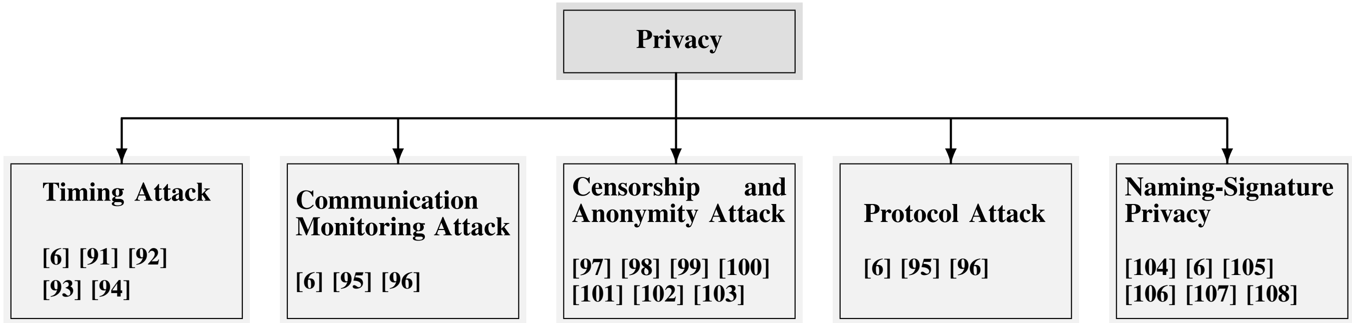

Fig. 10: Privacy Risks and their Countermeasures.

TABLE VII: Summary of Timing Attack Mitigations

	Acs *et al.* [91]	Mohaisen *et al.* [93], [94]	Chaabane *et al.* [6]
Approach	Delay for the first k interests	Delay for the first interest from each client	Delay for the first k interests
Mitigating Entity	Edge routers	Edge routers & access points	Edge routers
Granularity	Per content	Per client per content	Per content

addition, the router randomly delay satisfying a content for the first k-times it is requested, and deliver the content as soon as possible for the subsequent requests. This model reduces the latency for popular contents, but clients experience the extra delay for the first k-interests and this mechanism also requires extra state for maintaining the number of requests.

In [93], [94], Mohaisen *et al.* took a similar approach as above and proposed three variations of a mitigation technique for the timing attack. In the vanilla approach, an edge router fetches content chunks from the provider and stores the retrieval times for the corresponding first interests. The router also tracks the interest frequency of each requested privacy-sensitive content chunk. Each first interest for a cached content chunk from a new client (one who has not requested that content before) will be satisfied with a delay same as the recorded retrieval latency for the chunk. Clearly, the per-client state needed to be stored means that this approach will not scale with increasing number of clients. To reduce the storage requirements, a second approach proposed that the edge router stores only per-interface interest retrieval time history. Although this approach reduces state size, it also increases the potential of success of timing attack for an attacker on the same interface.

The last variation solved the shortcomings of the first two through cooperation between the access points/proxies and their corresponding connected edge routers. Here, the access point stores per-client state; and the router stores only per-face statistics. The decision to apply random delay is made by the router with the help of the downstream access point. The access point flags the interest from a new client to inform the router. The router delays the data reply for the flagged interests. We believe that despite the strengths of this scheme, the use of random delays goes against one of the core principles of ICN– leverage caching to reduce latency.

In [6], Chaabane *et al.* also proposed applying a delay–either on all requests for cached content, or on the first k-requests only–for mitigating timing attack. They also briefly discussed collaborative caching and random caching, to preserve cache privacy. Collaborative caching increases the anonymous clients set by increasing the number of clients that share a set of routers; thus it implicitly helps to preserve privacy. The authors provided no analysis of the caching approaches. We believe collaborative caching is a good direction for further exploration.

*2) **Summary and Future Directions in Timing Attack Mitigation:*** Table VII summarizes the proposed solutions to the timing attack. We present the referenced work, the proposed solution, and the entity in the network where the mitigation procedure is executed. We have not mentioned [92] as the authors have not really presented a mitigation strategy.

The majority of the proposed timing attack mitigation mechanisms [6], [91], [93], [94] apply an artificial delay during content forwarding, which makes them applicable to all architectures. Despite the effectiveness of this approach in misleading the adversary, it undermines the advantage of latency reduction due to caching. Another negative impact of this approach is degradation in clients' QoE, especially for the popular content objects.

One natural approach of coping with timing attack is designing an efficient collaborative caching mechanism, which not only increases the anonymity set of the clients but also improves system performance and reduces overall content retrieval latency. Moreover, this precludes the need for artificial delays. Chaabane *et al.* [6] have made an initial attempt in this direction. Network coding techniques can also be leveraged to design a secure and efficient content dissemination model by coding and dispersing the chunks.

B. Communication Monitoring Attack

In the communication monitoring attack [6], [95], [96], an attacker has access to the same edge router that the victim receives content from (similar to timing attack). However, here an attacker targets a specific victim and tries to identify the victim's requested contents; this is different from timing attack where the goal is to identify contents popularity. The attacker may know the victim's content consumption habits or specific characteristics, which differentiate the victim from other clients (e.g., language, region, or institutional affiliation).

*1) **Communication Monitoring Attack Mitigation Approaches**:* Lauinger *et al.* [95] proposed two types of request monitoring attacks under the stationary content popularity model with a constant request rate, employing non-invasive and invasive cache probing, respectively. The stationary popularity assumption states that the content popularity distribution does not change over large time periods, and the interest for a content is independent of previous interests. In the non-invasive cache probing model, the authors assumed that the attacker's requests do not change the router's cache state. The attacker (with prior knowledge of the victim's interests) frequently probes the shared router's cache.

The unrealistic assumption in the non-invasive model that the cache probing does not change the content popularity leads to the proposal of the invasive cache probing attack model. In the invasive model, a cache miss caused by the attacker at the shared router causes the requested content to be cached, hence the attacker needs to differentiate cache hits from cache misses. The authors also proposed a model for calculating the attacker cache-probing frequency.

The mitigation approaches proposed for monitoring attacks have been similar to that of the timing attacks. The authors in [95], [96] proposed selective caching, in which a content will be cached only if it reaches a specific popularity threshold. This is congruent with the assumption that privacy risk decreases as content popularity increases. Alternatively, a client can ensure privacy by establishing a secure tunnel with either the content provider or a trusted proxy [100], [103]. Another solution relies on the trustworthiness of the ISP to honor a client's request by not caching a content that is marked as privacy-sensitive by a provider. However, these approaches work under the assumptions that the ISP is trustworthy and the privacy-sensitive content are unpopularity, which may not always be valid assumptions.

Chaabane *et al.* explored attacks against content privacy in [6]. The authors introduced the monitoring and censorship attacks resulting from information exposure from caching routers. To cope with content privacy issues, the use of secure tunneling with symmetric/asymmetric encryption (like SSL/TLS). However, secure tunneling undermines the utility of caching, increasing core network load and content retrieval latency. As an alternative solution, the authors proposed broadcast encryption and proxy re-encryption, which in turn suffer from significant communication and computation overhead. Also, it is common knowledge that even with data encryption, monitoring of encrypted communication can leak information through traffic analysis.

In [92], Compagno *et al.* proposed a method to geographically localize a client. To mount this attack, the attacker uses several distributed hosts (zombies or bots) to request contents that they suspect a victim(s) may request. The aim is to identify corresponding cache or PIT hits. Precise time measurements and complete knowledge of the network topology and several other network properties are important in this attack. The authors noted that this attack is only effective when the victim requests unpopular content–a popular content is requested by many and hence monitoring a few entities is difficult. Although the study is interesting, the assumptions especially about complete network knowledge is strong and not practical. Also, the authors present no countermeasure.

*2) **Summary and Future Directions in Communication Monitoring Mitigation**:* Solutions to this attack disable caching of sensitive content either by creating a secure tunnel [100], [103] or with the clients flagging the requests as non-cacheable for privacy [95], [96]. These solutions are applicable for all ICN architectures. However, we believe that undermining network's caching capabilities is not a desired solution–it increases communication complexity and cost. Although we agree that secure tunneling is a viable approach, we believe an efficient tunneling mechanism should be designed, which at least allows partial content caching. Another direction to research is naming scheme randomization [97], which would make content-name prediction difficult for attackers. If manifests are used (metadata to create chunk names), they can contain encrypted information on how to request the random chunks, which only a legitimate client can decrypt. The requirement of decryption will also serve as an attack deterrent in general. Strengthening the vulnerable architectural features, such as scope, exclusion, and prefix matching would help reduce the attack scenarios for the affected schemes. Of course, they come at the expense of efficiency resulting from these features.

C. Anonymity and Censorship Mitigation

As in other networks, anonymous communication is important in ICN as well. Lack of anonymity may reveal critical information about the clients and the requested contents, which could be used to enable censorship. Unlike in IP networks, in ICN the packet carries the name of the content requested. The name in the interest (be it a human readable name, a hashed string, or a self-certifying name) can be used by an intermediate router to filter and drop it. The name can also be used by the first-hop router or proxy to censor the clients. As depicted in Fig. 12, an on-path adversary monitors the client's interest and compares the requested content name against its contents' blacklist for censorship. A match results in the request being dropped–an *effective censorship* mechanism.

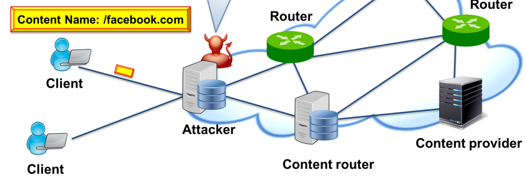

Fig. 12: Censorship risk due to lack of anonymity.

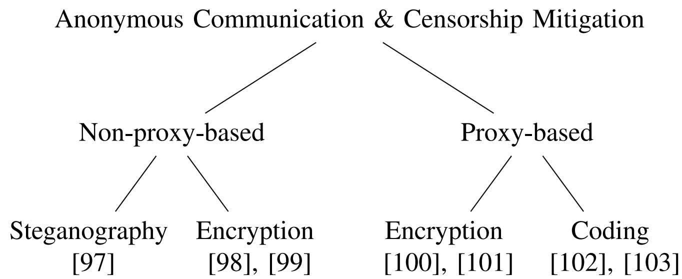

Fig. 13: Anonymous communication and censorship mitigation approaches are categorized into whether they use a proxy or not.

The exposure of the content name, and the semantic binding between the name and the content itself, raise new privacy and censorship concerns. Several anti-censorship mechanisms have been proposed in the literature [97], [99]–[103]. As it is illustrated in Fig. 13, we categorized the proposed mitigation mechanisms into *non-proxy-based* and *proxy-based* categories. The non-proxy-based mechanisms employ steganographic and/or encryption to provide privacy. In the proxy-based category, consumers interact with a proxy that is responsible for the client and name privacy (by creating encrypted proxy-client tunnels).

1) ***Non Proxy-based Mechanisms****:* The anti-censorship mechanisms we discuss under non-proxy-based category either employ steganographic techniques to obfuscate content names or use ephemeral identities and homomorphic cryptography to enhance clients privacy. Thus, we categorize these approaches into *steganographic* and *encryption* subcategories.

a) Mitigation Employing Steganography: In schemes that employ steganography, the objective is to obfuscate the content chunks' names, thus increasing the computational complexity of deciphering the chunks' names for the attackers, who are unaware of the name generation schemes. Arianfar *et al.* were one of the first to study this problem [97]. They proposed a name obfuscation scheme in which the content provider uses a secret cover file–a random file of the same size as the content. The provider splits the content and the cover into same sized blocks and runs an exclusive-or operation on all combinations of k (≥ 2) blocks of the content and the cover to create the corresponding encoded content chunks that are then published into the network. The name of an encoded chunk is the hash of the hashes of the names of the corresponding content and cover blocks respectively.

Utilizing a secure back channel, the provider sends each verified requesting client the necessary metadata, such as the content hash, the content's length in blocks, the corresponding cover blocks, the names, and the name generation algorithm. Using this meta-data the client generates the chunk names, requests them from the network, and deciphers them. Although the chunks and their names are publicly available, an adversary cannot decipher the content without the metadata; and it is computationally expensive to break the scheme to decipher the chunk names.

The size overhead of the scheme is significant. The cover file represents a 100% overhead, and must be transmitted via a secure back channel for each client–not scalable. In fact, if a secure back channel exists, that can be used to send the file itself.

b) Mitigations Employing Encryption: Approaches employing encryption either exploit temporary identities or leverage homomorphic cryptography to prevent client identity-based interest filtering. Elabidi *et al.* [98] proposed a privacy protection scheme, which enforces identity expiration. The system is composed of identity providers, trust verification providers, and digital identity protection authorities in addition to the standard network elements. The scheme provides users with ephemeral identifiers (by identity providers), which they communicate to the service providers. The service providers authenticate the users through a trust verification provider. The trust verification provider informs the digital identity protection authority when an ephemeral identity is used after its expiration. Though this design provides the useful "forgetfulness" property for the identities, a malicious service provider could disable access or filter requests from users by corrupting the ephemeral identities and preventing access for clients. Other issues with this scheme include need for several entities and the requirement of user authentication by a third-party service, which raise concerns of overhead and availability.

Fotiou *et al.* [99] proposed a mechanism to preserve content lookup privacy by leveraging homomorphic cryptography [111]. The scheme involves cooperation between providers, clients, and a hierarchical brokering system–a tree of brokering nodes. A provider publishes its content identifier to the brokering system, which disseminates the identifier-provider pair to the leaf brokering nodes. To locate a content, a client submits an encrypted query to the root broker node. By employing homomorphic cryptography, the query can be resolved by the brokering system without decryption. When the content is found, the client will be sent an encrypted response containing a pointer to the desired content provider.

In this scheme, a query includes a vector of sub-queries corresponding to the nodes in the brokering system. Each broker using its part in the sub-query to forward the query to its children recursively until the content is identified. A big pitfall of the mechanism is it requires 2^{h-1} decryption operations to locate a content at level h in the tree-hierarchy. In addition, considering the number of messages transmitted per query, the system scales poorly in the face of an increasing number of clients and contents.

2) ***Proxy-based Mechanisms****:* In proxy-based approaches, a client needs to interact and share a secret with a proxy (a network of proxies). The proxy is responsible for decrypting/decoding clients' requests, retrieving the requested content, and returning the encrypted/encoded content to the clients. The approaches are similar in spirit to the popular Tor (The onion routing protocol–the popular anti-censorship tool for IP networks). Based on how the layered-encryption is performed, we categorize the proposed proxy-based approaches

TABLE VIII: Summary of the Proposed Mechanisms for Anonymous Communication and Censorship Mitigation

Mechanism	**Approach**	**Infrastructure**	**Computation Complexity**
Non Proxy-Based Approaches			
Steganography			
Arianfar *et al.* [97]	Encoding interest by mixing content and cover file	Not Applicable	High (cover & exclusive-or)
Encryption			
Elabidi *et al.* [98]	Ephemeral identities for users	Requires three new entities	High (several interactions)
Fotiou *et al.* [99]	Hierarchical DNS based brokering model	Brokering Network	High (homomorphic cryptography)
Proxy-Based Approaches			
Encryption			
DiBenedetto *et al.* [100]	TOR based model – 2 layers of encryption	Two Proxies	Moderate (symmetric key)
Chung *et al.* [101]	TOR based model – 2 layers of encryption	Two Proxies	Moderate (symmetric key)
Coding			
Tao *et al.* [102]	Random linear network encoded interest	One Proxy	Moderate (RLNC + PKI)
Tourani *et al.* [103]	Huffman encoded interest	One Proxy	Low (Huffman coding)

into *encryption-based* and *coding-based*.

a) Encryption based Mitigation: ANDaNA [100], a tunneling-based anti-censorship protocol, uses two proxies– one proxy adjacent to the requester, and another proxy closer to the destination–to create a tunnel with two layers of encryption. By using ANDaNA, a client decouples its identity from its request. The first proxy is only aware of the client's identity (but not the content name), while the second proxy can only identify the requested content (not the client's identity). The interest travels unencrypted between the second proxy and the provider. The authors proposed an *asymmetric* version of the protocol where the two-layers of encryption are performed using the proxies public keys, with the packets decrypted by the proxies using their private keys. The content on its way back is encrypted using symmetric keys shared by each proxy with the client.

Due to the high cost of the PKI operations, the authors proposed a *symmetric* key based session-key model to replace PKI operation. Despite ANDaNA's usefulness as an anti-censorship tool, it induces significant delays in content delivery (ref. results in [100]) in comparison to Tor.These delays are caused, in part, by the process of setting up the secure channel.

In [101], Chung *et al.* took a similar approach to ANDaNA and Tor. In this approach, the client encrypts the interest packet with two symmetric keys that will be shared with two Anonymous Routers (ARs). The interest's encryption order follows the onion routing model. Different from conventional onion routing, an identifier (a hash of the content name) is embedded in the encrypted interest to enable cache utilization (i.e., CS-lookup) and interest aggregation (PIT lookup) at the first AR. The provider transmits the content to the closest (second) AR in plaintext. The content response on the way back may be cached on the second AR, which encrypts the content and forwards it to the first AR. The first AR decrypts the content for caching before re-encrypting it and forwarding it towards the client. Similar to ANDaNA, this scheme suffers from the same high cost of multiple per-packet encryptions/decryptions.

b) Coding based Mitigation: Unlike encryption-based anti-censorship approaches, the mechanisms in coding-based category employ coding techniques, such as random linear network coding and Huffman coding to protect clients privacy. In these mechanisms, a client only needs to interact with a single proxy, which performs interest and content encryption/decryption. Tao *et al.* [102] proposed a mechanism leverages ICN's inherent content chunking in conjunction with random linear network coding (RLNC). To request a content chunk, the client splits the interest into small chunks and encrypts a linear combination of the chunks with the public key of an intermediate trusted proxy. The proxy, after receiving enough interest chunks, reconstructs the original interest packet and sends it toward the content provider. The content provider follows the same approach as the client, splitting the content into small chunks and forwarding a linear combination of them towards the proxy. The two major concerns of this proposed scheme are a lack of cache utilization and the high cost of many asymmetric-key cryptographic operations.

Tourani *et al.* [103] addressed the ICN censorship problem, by proposing a client anonymity framework that leverages the prefix-free coding technique. In their proposed design, each client shares a unique Huffman coding table with an anonymizer, which may be collocated with the content provider or an intermediate trusted router. The client encodes the content chunk's name postfix (part of the name after the domain name) using its Huffman coding table, leaving the domain name in plaintext, to be used for routing. The authors also proposed ways to encode the whole name (when the domain is also censored) with the help of network entity, named the anonymizer.

When an encoded interest reaches the anonymizer, the name is decoded and the interest with the unencrypted name is forwarded to the content provider. The content provider sends the content chunk in plaintext to the anonymizer (caching can be leveraged on the path), which then encrypts the content name and forwards it to the client. The routers between the anonymizer and the provider can identify the content, but cannot identify the requester, while the routers from the anonymizer to the client cannot identify the name, thus preserving client privacy. The paper did not have a trade-off analysis between cache utilization and privacy preservation, and did not discuss the scope of potential differential cryptanalysis attacks. However, it is one of the approaches with the least overhead/latency.

*3) **Summary and Future Directions in Anonymity and Censorship Mitigation**:* Table VIII summarizes the existing anonymous communication mechanisms and presents their infrastructure requirements and computation complexities. Note that the technique proposed by Tourani *et al.* has the lowest computation complexity and infrastructure cost. Some of the existing anti-censorship solutions [100]–[103], have achieved anonymous communication through secure tunneling, where the content is encrypted between the providers/proxy and clients. Other approaches include a name obfuscation scheme [97] and a hierarchical brokering network [109] for anonymous content retrieval. Expensive cryptographic operations [97], [100], [101], requirement for a secure back channel [97], and undermining of in-network caching [100], [102], [103] are the main pitfalls of these mechanisms. Except the work by Fotiou [109] that targets architectures with brokering network (e.g., PSIRP and PURSUIT), other proposed solutions (e.g., tunneling, name obfuscation, and network coding based mechanisms) are applicable to all ICN architectures.

There are some potential directions for future research on cache utilization optimization and reduction in the cost of cryptographic operations. Applying cryptographic operations on a subset of content chunks to reduce cost has not yet been explored. Exploiting low-complexity network coding techniques [102], [103] instead of traditional cryptography would be a good idea to expand the applicability of tunneling schemes. This is especially important given that the majority of devices in the future will be resource-constrained devices (e.g., mobile devices, Internet of Things, etc.).

D. Discovery and Protocol Attacks

Discovery and protocol attacks are a result of intrinsic design features of CCN and NDN architectures (only applicable to these architectures). Some examples of these features are the interest packet scope field and the name-based matching used in NDN. Fig. 14 illustrates a discovery attack, in which an attacker probes all caches in a two-hop locality for content with prefixes */abc* and */XYZ*. In this subsection, we review two of the articles that addressed the pitfalls of these design features.

The authors in [95], [96] introduced an object-discovery attack, which abuses NDN's [7] prefix matching and exclusion pattern features. The attacker employs the prefix matching feature to probe for all cached content objects under a particular name prefix starting at the root of the namespace, say */www.google.com/*, and iteratively exploring it by using interests with exclusions and forcing intermediate routers to walk through the namespace. With the exclusion feature an attacker can discover the whole namespace (quickly for small namespaces) and also the names of cached content (additional monitoring attacks).

Chaabane *et al.* [6] also defined two protocol attacks based on prefix matching and scoping respectively. The prefix matching attack works as described by Lauinger *et al.* [95]. In the scoping attack, an attacker probes all the available content objects in nearby caches by leveraging the scope field in the interest packet. By carefully selecting the scope, the attacker can identify the content available in individual routers, thereby breaching the privacy of other clients. However, no solution has been proposed for these attacks except for the removal of the enabling features.

*1) **Summary and Future Directions in Discovery and Protocol Attacks**:* The use of prefix matching, exclusions, and the scope field are examples of features that can be attacked in some ICN architectures to probe for popular content objects and explore the content namespace. Prefix-matching feature is useful for legitimate clients with limited knowledge of their desired content name (e.g., when only a prefix of the content name is known). The scope field can also be employed by a legitimate client who would like to obtain a content only in the case that it is available in a nearby cache. Therefore, these features should not be completely eliminated from ICN, but instead should be redesigned with these threats in consideration. Potential solutions may be the use of rate-limiting requests for a specific namespace, similar to what is done by DNS servers today. We believe that there is a need for a comprehensive analysis, both analytical and experimental, of these features to identify their trade-offs.

Developing mechanisms to help routers to validate the integrity and authenticity of the z-filters needs research focus.

E. Name and Signature Privacy

Unlike the current Internet, several ICN architectures require the content to be explicitly requested by name. In ICN, names either follow a hierarchical human-readable or a self-certifying flat-name model. We refer readers to a survey on ICN naming and routing [70] for more details. In the human-readable naming convention, the content name exposes information about the content and the provider due to the inherent semantic binding.

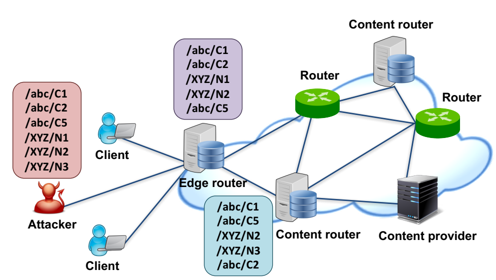

Fig. 14: Protocol attack scenario.

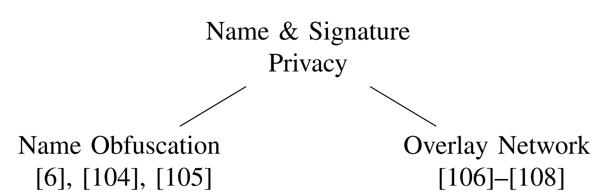

Fig. 15: Naming and signature privacy sub-classes and the state-of-the-art in censorship.

TABLE IX: Summary of the Proposed Approaches to Augment Name and Signature Privacy

Mechanism	Approach	Advantage	Drawback
Name Obfuscation			
Baugher *et al.* [104]	Cryptographic Content Hash-based Naming	Easy Authentication-Provenance	Not Suitable for Dynamic Content
Chaabane *et al.* [6]	Bloom Filter-based Naming & Group Signature	Increased Publisher Privacy	Bloom Filter Size & False Routing
Katsaros *et al.* [105]	Employing Ephemeral Names	Increased Publisher Privacy	Undermine Caching
Overlay Network			
Martinez *et al.* [106], [107]	Digital Identity in an Overlay Network	Privacy for Real Identities	Additional Infrastructure
Sollins [108]	Overlay Network with Identifier Resolution Service	Privacy for Real Identities	Lack of Compatibility Analysis

Fig. 15 illustrates our categorization of the literature in name and signature privacy starting with two broad categories: *name obfuscation* and *overlay network*. The proposed approaches in name obfuscation try to enhance name privacy by switching from the human-readable naming to machine-readable naming convention. In the overlay category the approaches use an overlay network in conjunction with a name resolution service to securely map the real identities to digital identities.

1) ***Name Obfuscation****:* The proposed name obfuscation use machine-readable naming schemes, which are generated by content digest, Bloom filter, and the use of ephemeral names. Cryptographic hash based naming was motivated by Baugher *et al.* [104]. The main advantage of such self-verifying names (names are cryptographic hash of the content) is the low cost of content authentication. In these schemes, a client obtains a content's (or chunk's) self-verifying name from a catalog that maps contents from their human-readable names to their hashes. The client stores the hashed name for future use and submits a request for the content corresponding to the hashed name into the network. It accepts the retrieved content if its cryptographic hash matches the self-verifying name from the catalog. This mechanism can also be used to preserve the privacy of the provider.

The authors noted that hash-based naming is only useful for read-only, cacheable data objects. Additionally, the use of the catalog to obtain self-verifying names requires the establishment of trust between clients and the catalog publisher, which requires creation of trusted infrastructure in the network a potential overhead.

Chaabane *et al.* in [6] discussed the privacy concerns emanating from the semantic correlation between the human-readable names and the content/provider identity, including potential leaks from digital signatures. They suggested the use of one Bloom filter for each name in the hierarchy to represent names without correlating with the content. To protect publisher privacy, they proposed different schemes such as confirmer signature, group signature, ring signature, and ephemeral identity. All of these solutions, except ephemeral identity, achieve signature privacy by increasing the cardinality of the anonymity-set of signers. Under ephemeral identity, frequently changing temporary identities used by a publisher prevent an attacker from identifying the publisher based on its signature. However, the probabilistic nature of Bloom filter and potential for false-positives may cause false routing and incorrect interest to content-chunk mapping. Furthermore, the size of the Bloom filters could be large and the lookup latency will increase with increasing levels in the name hierarchy.

Katsaros *et al.* also investigated ephemeral names for content to improve publisher privacy [105]. Despite the benefits of using ephemeral names for content providers, temporary naming undermines the network's caching capability. Contents with ephemeral names will expire and will be purged from the caches, hence they will not be available to meet clients' requests; this is especially true for popular content.

2) ***Overlay Network****:* This category of secure naming leverages an overlay network in which entities are associated with identities that are only known in that domain. The overlay network uses a name resolution service to map the entities to their identities. Martinez *et al.* [106], [107] proposed such as scheme for privacy and untraceability. Each network entity (users, machines, services, hardware) is associated with a digital identity and a domain. Each domain is equipped with a Domain Trust Entity (DTE), which manages entity-identifier associations and identifier authentication. The DTEs form an interconnected infrastructure, which facilitates identity-based communication. For two entities to establish a communication channel, the first entity authenticates itself to the DTE infrastructure and submits a query seeking the other. The DTE infrastructure processes the query and returns the identifier of the other entity. The identifiers are used to establish a secure tunnel through the DTEs. Although this overlay network preserves the entities' identities, the network's security can be undermined by compromised DTEs, which themselves form additional network infrastructure.

Sollins [108] discussed the design issues with names in ICN and proposed an overlay naming system for content identification. The naming system uses the scope of the ID space (local, global), the ID syntax (size, structure, character set), and the ID structure (flat, hierarchical, composite). In addition, identifier-object mapping requires the existence of a naming authority to enforce ID lifetime and uniqueness and a name resolution system. The author designed a Pervasive Persistent Object ID (PPOID), based on the principles of layering and modularity. With PPOID, a human-readable identifier is mapped into an ID space, which resolves to an ICN identifier. Simple and expressive user-friendly identifiers at the top layer are mapped onto machine-readable identifiers for real-time resolution and delivery. However, the author did not discuss the applicability of this naming system to the existing popular ICN architectures and challenges.

3) ***Summary and Future Directions in Name and Signature Privacy****:* Table IX summarizes the proposed mechanisms for preserving name and signature privacy. We present the referenced work, their approaches to augment the naming and signature privacy and their advantages along with their drawbacks. The proposed approaches for name and signature privacy include overlay-based network [106]–[108], self-verifying names [104], and hierarchical Bloom filter based naming [6]. The drawbacks of the overlay-based models is their dependency on trusted entities and additional latency for resolving content names. The proposed hierarchical Bloom filter naming approach [6], suffers from false positives. The self-verifying naming approach [104] is only applicable to read-only content, not to dynamic contents, which are generated upon request. For dynamic content no catalog can be generated ahead of time.

We believe an efficient approach in this context could be for the provider and the user to cloak their identities by using several certificates to map to several identities and using the identities at random. This is similar to the k-anonymity mechanism used to create an anonymity-set for an identity.

4. Access Control in ICN

In this section, we explore the proposed access control (AC) enforcement mechanisms for ICNs. The unique characteristics of ICN, such as name based routing and in-network caching make AC management more important. By design most ICN architectures are requesting host agnostic. Thus, once content is disseminated in the network it can be cached and disseminated by network routers to satisfy requests without the routers checking if the requesting entity can access the content. This in turn could lead to content providers losing control over who accesses their content. Researchers in the domain have recently started exploring this problem.

As depicted in Fig. 16, we categorize the-state-of-the-art in ICN access control based on whether they use a particular encryption technique or are independent of the underlying encryption used as *encryption-based* and *encryption independent* categories. The encryption-based category is further subdivided, based on the type of encryption into *broadcast encryption*, *PKI*, *attribute-based*, and *identity-based* subcategories. The encryption independent category presents approaches that present AC frameworks that can use any encryption algorithm for performing AC. We discuss these categories in more details in what follows.

A. Encryption-Based Access Control

All proposed encryption-based approaches are conceptually similar–the content providers encrypt their content before disseminating them into the network. Clients need to authenticate themselves and obtain the content decryption keys to be able to decrypt and consume the content.

1) ***Broadcast Encryption Access Control:*** Broadcast encryption allows a content provider to encrypt its content using a single key for all clients; the clients use their individual keys to decrypt the content. It also allow efficient revocation of the clients (without content re-encryption). A secure content delivery framework, which waives the necessity of an online authentication service was proposed by Misra *et al.* [112], [113]. The framework uses the (n, t)-Shamir's secret sharing based broadcast encryption to enforce AC. The framework's strength is that it needs no additional authorization entity nor incurs extra computational overhead at the routers.

For secure content delivery, the provider encrypts the content with a symmetric content encryption key and disseminates it into the network. In addition, the provider generates and disseminates a small amount of keying material (called enabling block, EB, and containing t-key shares) into the network. Only authorized clients can use the EB and their individual keys to decrypt the content encryption key and decrypt the content after that. The EB is requested by the client along with the content, and is cacheable.

Client revocation is achieved by updating the EB by the replacement of one of the key shares with the revoked client's share, which disables the revoked client from decrypting the symmetric key. In this mechanism, the EB is an overhead (minor for large contents, but significant for small ones). The EB update on client revocation also consumes network bandwidth.

2) ***PKI-Based Access Control:*** As shown in Fig 17, we categorize the PKI-based mechanisms into *session-based*, *proxy re-encryption*, and *probabilistic* subcategories.

a) Session-Based Access Control: The state-of-the-art in session-based AC suggests establishment of a secure session between a client-provider pair after client authentication and authorization. Within a secure session, the client can request content from the provider. Renault *et al.* [114], [115] proposed a session-based access control mechanism for NetInf. This mechanism requires a security controller, collocated with each content storage node, to check the access rights of clients. A client and the security controller establish a secure channel and exchange public keys using the Diffie-Hellman key exchange protocol, thus requiring no additional infrastructure.

The client requests a content using the content ID and its own public key (the public key may be omitted for publicly available content). On receiving a client's request, the security controller performs challenge-response with the client to verify the client's identity. Upon verification, the controller checks whether the client is authorized to access the content before forwarding the data; revocation can happen at this point. The interactions take place in a secure session; the session ends if either party explicitly requests its termination.

The main drawbacks of this scheme are: the cache between the client and the controller is effectively unusable and the need for the secure tunnel between the controller and the client for the duration of communication. The authors discussed the security of this mechanism against several well-known attacks, however they did not explore the potential for DoS/DDoS attack. A client can open one/more idle connections with the controller and exhaust the resources. Also, this connection-oriented set-up is antithetical to the connectionless ICN paradigm.

Wang *et al.* [116] designed a current IP-like session-based AC mechanism. The authors illustrated their design using the

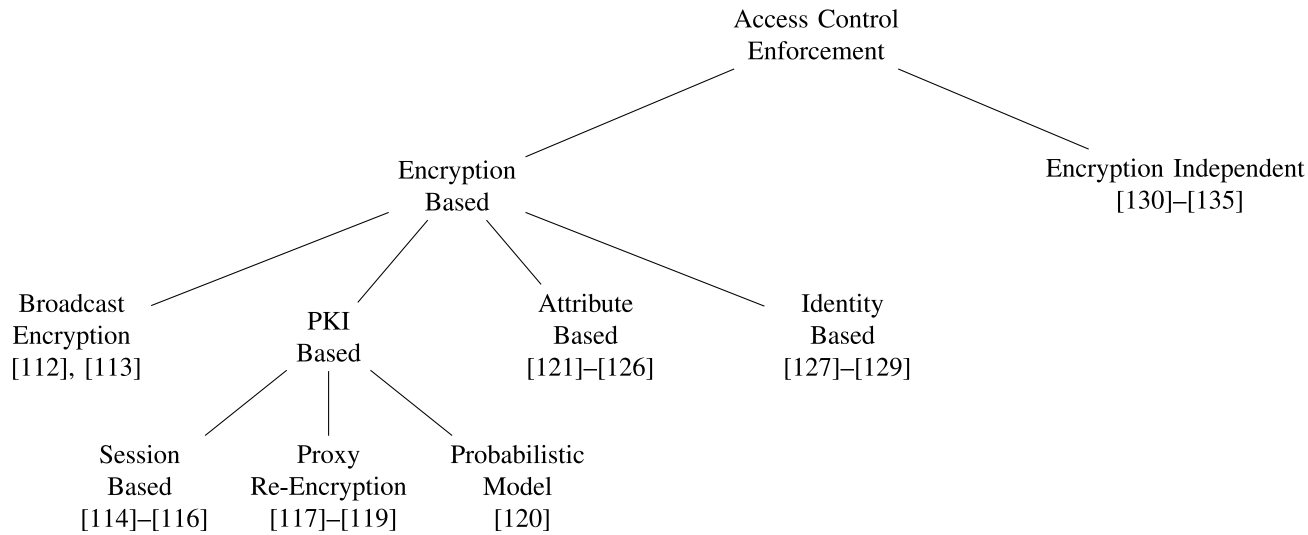

Fig. 16: A classification of existing access control enforcement mechanisms.

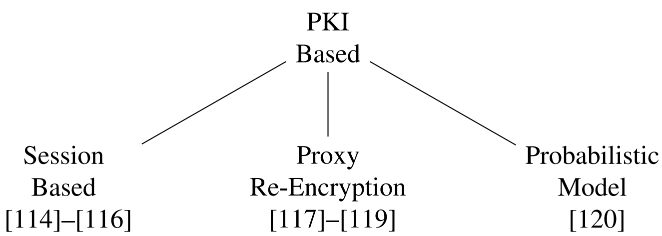

Fig. 17: A classification of the existing PKI-based access control enforcement mechanisms.

example of an online social network (OSN). A user registers in the OSN (content provider) by sharing a symmetric key and its credentials with the OSN service. Upon registration, the OSN provides a unique ID for the user. The client logs in to interact with the OSN. It generates a new symmetric key and sends it to the OSN along with the login information. The OSN then assigns a session ID to the client and stores a tuple consisting of the session ID, the client ID, and the new key.

To upload content, a client needs to be authorized first. After authorization, the client encrypts the content with the previously shared symmetric key, then forwards it to the OSN along with its desired AC policy. The OSN decrypts the content and re-encrypts the content with a newly generated symmetric key. Other clients request the content using its public name (obtained from a search in the OSN or a search engine). The OSN, authorizes the client and its access to the content and returns the content's secure network addressable name, the symmetric key to decrypt the content, and the required metadata encrypted with the requester's session key. The requesting authorized client decrypts the message and requests the content by the secure name. To prevent the public name-secure name correlation and access by revoked clients, the OSN changes the secure name at regular intervals.

This scheme undermines the potency of in-network caching as renaming a popular content effectively invalidates it in the cache. It also results in a content existing under several names in the network, which violates the ICN's principle of content name immutability. Also, content access overhead is high given that the process has to be repeated for each content.

b) Proxy Re-Encryption-Based Access Control: In proxy re-encryption-based AC, a piece of information is re-encrypted by an intermediate proxy (a third party or an intermediate router) for each client. Wood *et al.* [117] proposed a flexible mechanism for secure end-to-end communication, leveraging a combination of proxy re-encryption and identity-based encryption. The content provider encrypts content using a symmetric key before dissemination. A client may obtain a content from either a cache or the content provider. Upon receiving the encrypted content, the client requests the symmetric key from the content provider. The provider validates the client's legitimacy and access level and sends the symmetric key to a validated client, encrypted with the client's identity. The client extracts the received key and decrypts the content.

The proposed scheme reduces the cost of cryptography as only the symmetric key is encrypted individually for each client, the content is not. However, contact with the content provider is required with each request, even if the content can be retrieved from a cache. This undermines content availability in the case of the provider's unavailability.

Mangili *et al.* [118] proposed a framework for AC and track-ability in which content is broken into partitions and further into fragments allowing two layers of encryption by providers. A provider encrypts the fragments into a chunk using a symmetric key that will be stored in the encrypted chunk. In the second-layer of encryption, used for confidentiality and collusion prevention, a key-chain is generated using the "key-regression" key derivation algorithm [136]. An authenticated consumer regenerates the second-layer key by using a secret obtained from the provider. To prevent collusion, the provider encrypts the first-layer encrypted chunks with different second-layer keys (per user or group of users keys), which will be generates only for authorized clients.

On client revocation, the provider generates a new second-layer key and publishes the re-encrypted data. The framework requires caching routers to regularly query the provider for newly encrypted chunks to replace the old ones. Despite leveraging in-network caching, clients are required to perform per content authentication at the providers; requiring always online providers. Furthermore, legitimate clients may end up with fragmented sets of chunks with each fragment of chunks encrypted with a different key. This would require a client to download all the corresponding keys and identify which key decrypts which fragment.

Zheng *et al.* [119] proposed an AC mechanism which requires edge routers to perform content encryption. The process starts with the publisher encrypting the content with its public key and a random key k_1. Upon a client's request for a content, the edge router selects a random key k_2, and re-encrypts the encrypted content (as in proxy re-encryption). The random key k_2 is encrypted by the publisher's public key and signed by the edge router, and is attached to the content to be sent to the client. To decrypt the content, the client sends the encrypted k_2, the content name, and its identity to the publisher. The publisher validates the client's identity and access level and upon validation uses its private key, along with k_1 and k_2 to generate the content decryption key k for the client. Upon receiving k, the client may decrypt the content. Due to the randomness of the k_2 generated with each request, the decryption key k will be different for each client.

The performance analysis in the paper shows that the edge router's re-encryption operation takes about 10 seconds for a small content (256MB). The need to use edge routers' resources for encryption undermines the scalability of this solution, especially since the majority of the future Internet traffic is expected to consist of large multimedia content.

c) Probabilistic Access Control: In the probabilistic AC, the network is equipped with Bloom filters for storing the authorized clients' public keys. The intermediate routers use these Bloom filters to block unauthorized requests, which helps reduce clients' authentication cost. Chen *et al.* proposed a probabilistic structure for encryption-based AC in [120]. Publishers and clients are equipped with public-private key-pairs, and each client initially subscribes to a publisher by sending an interest. The publisher stores a record for each registered client, noting the client's credentials. For efficiency the authors suggested PKI-bootstrapped symmetric key exchange between the publisher and the client. The content requested by the client is delivered encrypted. After receiving the content, the client authenticates itself to the publisher to securely obtain the symmetric decryption key.

The authorized clients' public keys are put into a Bloom filter, which is transmitted to network routers to allow them to filter invalid requests. The interest of a client whose public key is not indexable in the content's Bloom filter is dropped. Although this procedure reduces network load, the recommended client revocation incurs costly content re-encryption and distribution. The approach has two other drawbacks: Bloom filter's suffer from false positives–an unauthorized client's request can be satisfied with a small probability. The size of the filters could rise rapidly with increasing number of clients. Second, is the need for authentication of the client at the publisher to obtain the symmetric key. This requires an *always-online* publisher (or another entity) to verify client credentials, which is difficult to guarantee.

*3) **Attribute-Based Access Control**:* In attribute-based AC, a content is encrypted with a set of its attributes. Each client is assigned a key, generated from the client's set of attributes. The client can consume the content if she can use her attributes to decrypt the content-access policy, which is either embedded in the encrypted content or the decryption key. Ion *et al.* [121] proposed an attributed-based encryption (ABE) mechanism for AC enforcement that used either the key-policy or the ciphertext-policy based encryption models.

In the key-policy model, the content is encrypted with a key derived from the content attributes, and the access policy is embedded in the decryption key. A key authority grants different decryption keys to clients, based on their attributes and access policies. In the ciphertext-policy model, the AC policy contains the required client attributes and is attached to the encrypted content. The key authority issues a key for each client, in this case derived from the client's attributes. Attribute and identity based encryption mechanisms require elaborate revocation procedures. The authors did not describe the process of client revocation, and did not analyze the performance and efficiency of revocation in the scheme.

Li *et al.* [122]–[124] used attribute-based encryption for access control enforcement in ICN. In the proposed scheme, a trusted third party defines and manages the subject and object attributes by creating attribute ontology for each (ontology in this context is the universe of all attributes). As the cached contents are available to all users, to prevent unauthorized access, the authors proposed a naming scheme, which preserves the privacy of the AC policy. To publish a content, the publisher generates a random symmetric key with which it encrypts the content. The encrypted content, along with its corresponding metadata, is disseminated into the network.

The publisher also generates an AC policy from the attributes defined by the trusted third party; the access policy then defines which clients are authorized to access the content. The publisher uses the AC policy to encrypt the symmetric key, which encrypts the content. This encrypted symmetric key is the content name. A client needs to retrieve the content name (possibly through some kind of domain name service) and extract the symmetric key using its attributes (only possible by an authorized client). Despite its low overhead, the applicability of this scheme is questionable due to the proposed naming scheme; the content name is generated by encrypting the symmetric key with the AC policy. Compromise of the symmetric key would necessitate re-keying and hence change the content name, which undermines the spirit of immutable naming in ICN. Also, client revocation remains a challenge.

Da Silva *et al.* [125] proposed an AC mechanism using attribute-based encryption for instantaneous access revocation. The authors suggested the use of Ciphertext-policy ABE, in which the access policy, generated by the provider, is embedded inside the encrypted content. The content is encrypted with the required authorization attributes, which are stored in content routers. Each content has an access policy, which is stored at a proxy. Only the proxy can decrypt the access policy.

When the client registers with the application, it receives a key (based on its attributes) and an ID. For content retrieval, the client sends two interests: the first one retrieves the encrypted content (from the publisher or a cache), and the second, which includes the client ID and the content name, is sent to the proxy to decrypt the access policy. The proxy authenticates the client and decrypts the access policy on the client's behalf; this decrypted policy is forwarded back to the client without being cached in the network. The client can decrypt the content if its attributes satisfy the access policy retrieved from the proxy. In order to perform immediate revocation, the publisher notifies its proxy of each revoked client. Because each client should be authenticated by the proxy for access policy decryption, the proxy can deny access to the revoked clients. The main drawback of this mechanism is its requirement for the third-party authentication by the proxy–a single point of failure that needs to be always online.

Raykova *et al.* [126] proposed authentication-based AC for pub/sub networks using distributed trust authorities, which play the roles of certificate and authorization authorities. Before publishing a content, a publisher protects the payload using the ciphertext-policy ABE. Only a subscriber with the required attributes may decrypt the ciphertext. In the pub/sub network, broker nodes match the published content to the subscriber's interest. However, this matching process leaks some information such as the requested content name and the requester's subscription.

To limit this information exposure and preserve subscribers' privacy, the authors suggested using a unique hashing function to hash interests and content tags. These brokers may then use these hashed values instead of the raw interests and content tags. To limit the authorized brokers' access to these values, the hashed values are also protected using ABE. The overhead of interest hashing, ABE, and the corresponding per-hop hash matching procedure increase content retrieval latency significantly, thus undermining this approach.

*4) **Identity-Based Access Control:*** In identity-based cryptography, either entities' identities or the content names are used as the public keys. This allows providers or the network to authenticate a client using her identity. Hamdane *et al.* [127] proposed an identity-based cryptography AC system based on hierarchical tree-based content naming in which the entire subtree of a parent node inherits the AC policy of the parent. In order to control the access to a sub-tree's content, the root of the sub-tree, is assigned an encryption/decryption key pair and a symmetric content encryption key.

The symmetric key is encrypted using the root's encryption key. To give an entity read access on a content, the root decryption key is encrypted using the authorized entity's public key. Upon successful authorization, the entity retrieves the encrypted symmetric key. An entity with write access must also have access to the root's encryption key. A lazy entity revocation can be performed in this scheme, which requires the root's encryption/decryption key pair to be updated. This prevents a revoked client from accessing new content, however the client can access the contents published before revocation. The old decryption key needs to be encrypted with the new key, so that all newly added clients may access previously published content. Considering that this procedure creates a chain of encrypted keys, each revocation makes content access more expensive.

To overcome the above drawback, the authors proposed a credential and encryption-based AC mechanism in [128]. The proposed mechanism introduces an AC manager (ACM), which possesses the root key for a namespace and defines and enforces AC policies for the namespace. Clients possess read and/or write capabilities so they can publish content and/or request content. To publish a content, a publisher queries the repository to check whether the target namespace is subject to AC. In the case that the name is protected, the publisher forwards its credentials, signed with its private key to the ACM, and requests an encryption and decryption key pair. The ACM returns the encryption and decryption keys to an authorized publisher.

The publisher encrypts the content with a generated symmetric key, encrypts the symmetric key with the encryption key, and sends the encrypted content and the encrypted key to the repository to be cached. When a client requests the content, the encrypted data will be delivered along with the access policy. The client then forwards its credentials to the ACM and retrieves the decryption key, if its credentials satisfy the access policy. However, the authors neglected the client revocation problem. If a client that has access to several decryption keys is revoked, it can still keep using the keys. To revoke it, all the corresponding publisher contents need to be re-keyed. Also, the authors do not mention how the ACM verifies if a client is revoked or not and who performs the revocation.

Aiash *et al.* [129] proposed an identity-based AC mechanism for NetInf. This mechanism involves two steps: registration and the authorization. In the registration step, all clients and publishers share their public keys (i.e., identities) with the name resolution service (NRS). Upon a client's authentication, the NRS generates a sub-token (subscriber token) and encrypts it with the client's public key. To retrieve a content, a client retrieves both its (encrypted) token and a pointer to the content object from the NRS. The NRS replies with the identity of the publisher, and the client may use its token to request the data from the publisher.

On receiving a client request, the publisher first queries the NRS to verify the authenticity of the sub-token. After token authentication, the publisher sends a challenge to the client to verify its identity. After authenticating the client, the publisher verifies the client's token against the content token, and if the client is authorized to access the content it returns the content.

This scheme's drawback is the communication overhead introduced by both frequent queries to the NRS to verify tokens and the challenge-response interaction between the client and the publisher. Also, in this mechanism the authority of making content AC decisions lies with the NRS, instead of the publisher.

B. Encryption Independent Approaches to Access Control

In this category, we discuss approaches where the AC mechanism is proposed as a generic framework and can use different available encryption mechanisms. We pay attention to the frameworks in these approaches without going into the details of the encryption mechanism used. For example, Kurihara *et al.* [130] proposed an AC framework that can use any well-known cryptographic scheme. This framework utilizes CCN's *manifest* feature, and can leverage AC mechanisms, such as group-based and broadcast-based AC. The entities in the framework are content providers, clients, an encryption and dissemination server, a key manager, and an access policy manager. The key manager generates a symmetric key (*nonce key*) for content encryption and sends it to the encryption and dissemination server, which performs content encryption and dissemination.

The nonce key is then encrypted by another encryption algorithm depending on the underlying AC structure, e.g., broadcast encryption, attribute-based encryption, or session-based encryption. The decapsulation key, the key that decrypts the nonce key, is then encrypted by the access policy manager under the authorized client's public key and published into the network. For content retrieval, an authorized client (authorization happens at the content provider using the client's credentials) downloads the encrypted content, uses the content manifest to locate the decapsulation key, and decrypts the content. The authors suggested using lazy revocation, which would allow revoked clients access to previously published content until it is re-encrypted and re-disseminated. Overcoming this would require a significant overload–a downside for most proposed AC schemes.

Fotiou *et al.* [131] proposed an AC enforcement method for rendezvous-based ICN architectures. The model proposes the use of an access control provider (ACP), which interacts with publishers, rendezvous nodes (RNs), and subscribers to create AC policies and authenticate subscribers against the policy. A publisher first provides its AC policy to the ACP, which assigns a URI to the policy. The publisher forwards the content, along with the policy URI, to the RNs. A requesting subscriber will receive the URI of the AC as well as a nonce from the RN. Simultaneously, the RN forwards the nonce and the URI of the relevant AC policy to the ACP. Upon receiving the client's credentials, the ACP verifies it against the policy and informs the RN whether the client is permitted access. If permitted, the RN sends the content to the client.

This approach has additional computation and communication overhead at RNs and/or routers which will increase response latency. It requires the RN to store the AC policy URI for each content. In addition, there is a need for a trusted ACP, which may become a single point of failure. Finally, the mechanism for subscriber revocation has not been discussed.

Singh [132] proposed a trust-based approach for AC in pub/sub networks. In this scheme, a client has to establish trust with a broker, an intermediate entity that authenticates clients and publishers. During registration, a new client or publisher presents its credentials and attributes to the broker, which results in the establishment of trust. The publisher defines an access policy and submits it to its broker.

A registered client requests content from its local broker. If the local broker does not have the content, it returns the information needed to locate the correct broker. The broker possessing the content evaluates the trust and AC level of the client. Despite the theoretically wide applicability of the proposed scheme, the authors did not discuss client identification, and access level identification/verification, client revocation, communication overhead, and the broker network creation and management of publisher-broker network interactions.

Tan *et al.* [133] proposed a solution to copyright protection problem in the form of an AC mechanism. They proposed to divide protected content into two portions: a large cacheable portion, and a smaller portion which remains at the publisher. Each client retrieves the small portion from the publisher to reconstruct the content, thereby the publisher may enforce AC on its content. In order to provide track-ability of authorized clients, the authors suggested that the small portion be unique to each client; each client's copy stored at the publisher.

The request for this small portion allows publisher to track a client. According to the authors, this also allows identification of a malicious client that leaks its portion to an illegitimate user. However, this verification may not be possible. If a malicious authorized client gives its content to an illegitimate user and the user downloads the rest of its content from the publisher, there is no way that the publisher can know, which user's small share was used. Another drawback of this mechanism is also the need for an always online provider.

Ghali *et al.* [134] tackled the AC problem using an interest-based model, in contrast to popular encryption-based approaches. The two major design aspects of this approach are (1) name obfuscation, and (2) authorized disclosure. The former prevents unauthorized clients from obtaining the content name, the latter requires each entity responding to a content request to perform authentication/authorization on the publisher's behalf. The authors proposed encryption-based and hash-based name obfuscation, in which each authorized client (either individually or as part of a group) encrypts (with a symmetric key) or hashes a suffix of the content name with a key shared with the provider.

The interest for a content carries a nonce, a time-stamp, and a client identifier in its payload, and is signed by the client using the client's private key (individual/group). The provider, upon receiving an interest, verifies the client's signature and fetches the client's key to decrypt the encrypted portion of the content name. The provider attaches the group's public key to the content (for signature verification) and forwards it to the client. On receiving a content, the on-path routers, store the

TABLE X: Summary and Classification of the Proposed Access Control Mechanisms

Mechanism	Communication Overhead	Computation Burden			Additional Infrastructure	Client Revocation	Cache Utilization	Access Control Enforcement
		Provider	Network	Client				
Encryption-Based								
Broadcast Encryption								
Misra *et al.* [112], [113]	✓	✗	✗	✓	Not Required	Threshold Based	Yes	Client
Session-Based								
Renault *et al.* [114], [115]	✓	✗	✗	✗	Required	Not Considered	No	Network
Wang *et al.* [116]	✓	✓	✗	✗	Not Required	Not Considered	No	Provider
Proxy Re-Encryption								
Wood *et al.* [117]	✓	✓	✗	✗	Not Required	Not Considered	Yes	Provider
Mangili *et al.* [118]	✓	✓	✗	✓	Not Required	Partial Re-encryption	Yes	Client
Zheng *et al.* [119]	✓	✓	✓	✗	Not Required	Not Considered	Yes	Network
Probabilistic Model								
Chen *et al.* [120]	✓	✓	✓	✓	Not Required	Daily Re-encryption	Limited	Provider/Network
Attribute-Based Encryption								
Ion *et al.* [121]	✓	✗	✗	✗	Required	Not Considered	Yes	Client
Li *et al.* [122]–[124]	✓	✓	✗	✓	Required	Not Considered	Yes	Client
Da Silva *et al.* [125]	✓	✗	✓	✗	Required	Key Update per Revoc.	Yes	Network
Raykova *et al.* [126]	✗	✓	✗	✓	Required	Not Considered	No	Client
Identity-Based Encryption								
Hamdane *et al.* [127]	✓	✗	✗	✗	Not Required	System Re-key	Yes	Provider
Hamdane *et al.* [128]	✓	✗	✗	✓	Required	Not Considered	Yes	Network
Aiash *et al.* [129]	✓	✗	✗	✗	Required	Not Considered	No	Provider
Encryption-Independent								
Kurihara *et al.* [130]	✓	✗	✓	✗	Required	Lazy Revocation	Yes	Provider
Fotiou *et al.* [131]	✓	✗	✓	✗	Required	Not Considered	Yes	Network
Singh [132]	✓	✗	✓	✗	Required	Not Considered	Yes	Network
Tan *et al.* [133]	✓	✓	✗	✗	Not Required	Considered	Yes	Provider
Ghali *et al.* [134]	✗	✓	✓	✓	Not Required	Not Considered	Limited	Provider/Network
Li *et al.* [135]	✓	✓	✓	✗	Not Required	Not Considered	Yes	Provider

obfuscated content name and the public key to authenticate the subsequent requests for the same content from the same group of clients. If the request cannot be authenticated it is dropped.

This approach has several concerns. Obfuscated content names may result in several copies of a content being stored, undermining caching effectiveness. The use of hashing for name obfuscation would also require the provider to pre-compute the hashed content names for each individual and group–not computation and storage efficient. A revoked client from a group can still request content until the provider revokes its membership and updates the group's keying material.

Li *et al.* [135] designed a lightweight digital signature and AC scheme for NDN. The access policies are enforced using provider generated tokens–metadata that indicate access levels. Two private tokens, per authorized entity, enable content access and integrity verification. Upon an entity's request for a token, the provider encrypts the token (generated by hashing a key vector) based on the requester's access level.

The provider combines a Merkle hash tree (generated using content blocks and tokens) and a new key vector to create hash-based signatures. For signature verification, a client regenerates the Merkle hash tree, using the retrieved content and the new token, and combines it with the obtained signature to extract the original signing tokens. The signature is valid if this token matches the token obtained from the content provider.

Although the proposed algorithm is faster than conventional RSA signing, the entities must synchronize with the provider for the correct version of the token. The provider also must store, for each content, at least three tokens and their corresponding key vectors at any time. The tokens also need to be freshened at regular intervals for better security. Finally, client revocation, one of the most important concerns of AC in ICN, has not been discussed in this article.

C. Summary and Future Directions in Access Control

Table X presents a summary of the proposed AC mechanisms for ICN. It compares the existing mechanisms on the basis of their overhead: communication and computation, and the entities that bear the computation burden. Client revocation method, ability of cache utilization, and the entities that enforce AC are other comparison features in Table X.

In this section, we reviewed the existing research in ICN AC enforcement and specifically focused on models including broadcast encryption-based [112], [113], attribute-based [121]–[126], identity-based [127]–[129] session-based [114]–[116], proxy re-encryption-based [117]–[119], and others [131]–[135] models. Although almost all the proposed mechanisms introduce communication overhead, some of the proposed mechanisms [129], [131] require extensive interactions between an AC manager and other network entities in order to enforce access constraints. These interactions not only increase communication and computation overhead, but also require additional infrastructure.

We believe that the availability of a content in caches is undermined significantly if content access requires authentication and/or authorization from an always-online server, which is difficult to guarantee. To truly exploit ICN's intrinsic provisions for content availability, an AC mechanism should refrain from using an always-online entity. The work by Misra *et al.* [113] is the first attempt in this direction.

Access right revocation is the other major concern of current proposals for ICN AC management. Attribute-based mechanisms [121]–[123], [125]–[129], in general, either take the costly and inefficient approach of per-revocation re-keying, or allow clients to continue accessing cached content even after revocation. Although we believe that the latter approach is more acceptable, as it imposes less complexity, efficient access revocation is a key design factor for scalable AC in ICNs. Some of the proposed mechanisms [114], [119], [120], [125], [128], [131], [132], [134] require the network (routers) to enforce AC and authenticate clients. The fact that the intermediate routers have to perform authentication procedure undermines the scalability of these mechanisms. There is scope for improvements on all these noted fronts.

We note that some of the proposed mechanisms target specific architectures, such as pub/sub based architectures [126], [131], [132], NetInf [114], [115], [129], or CCN/NDN [130], [135]. However, the majority of the proposed mechanisms are generic and can apply to all ICN architectures. There are some exceptions. The work by Kurihara *et al.* [130] is applicable to architectures with the manifest feature (e.g., CCN). The mechanisms proposed by Li *et al.* [122], [123] and Ghali *et al.* [134] modify the content name and hence are only applicable to architectures with flexible content naming scheme. The proposal by Hamdane *et al.* [127] is limited to architectures with a hierarchical naming scheme.

5. Conclusions and Lessons Learned

In this survey, we have comprehensively explored the existing work in the domain of ICN security. We divided the content into three major sub-domains: security, privacy, and access control enforcement. We reviewed the existing work in each sub-domain, and highlighted the drawbacks and benefits of each proposed solution. Additionally, we provided potential future research directions to explore to overcome the mentioned shortcomings.

In the security section, we explored attacks such as denial of service, content poisoning, and cache pollution, and also presented the proposed models for secure naming, routing, and applications. The majority of the existing works in this sub-domain aim to prevent adversaries from degrading the user QoS and QoE through malicious behavior, such as interest flooding, cache pollution, and packet forgery. However, the negative impacts of these solutions on legitimate clients have not been studied in depth. Among these attacks, DoS is the most widespread and the easiest to mount. A simple rate limiting approach can mitigate the impact of the attack to some extent, however, it also can starve legitimate clients. Thwarting content poisoning attack, despite its detection simplicity, requires computational resources at the intermediate routers, which makes it more severe.

ICN privacy threats can affect content, caches, and the clients. Timing and monitoring attacks specifically target cached content in the router shared between a victim and an attacker threatening both the victim's and the cache's privacy. Proposed countermeasures such as applying random delay can protect the attack targets at the expense of latency. Protocol attacks caused by ICN protocol design flaws target cache privacy, while naming and signature privacy attacks target the name and signer privacy respectively. Among the privacy risks that we have explored, we believe requested content anonymity is of the utmost importance in ICNs.

The availability of content replicas at various locations outside the publisher's control creates need for more sophisticated access control mechanisms for ICN. The majority of the access control mechanisms in the state of the art rely on the existence of an online service to authorize each content request. However, per-content online authorization dramatically increases the communication overhead, and can also undermine content availability if the authorization service goes down; regardless of the presence of the desired content in a nearby cache. There is a need for an access control mechanism that guarantees the usability of the cached content, regardless of the content provider's availability. This can be achieved through enforcing access control by network elements that cache the content. However, the computation and communication overheads at the routers of the authentication and authorization processes can become excessive.

In what follows, we identify the lessons we have learned while reviewing the state of the art in ICN security.

First, the negative impacts of proposed security protocols on legitimate clients can be significant and this impact's mitigation should be further investigated. Approaches such as rate limiting on suspicious interfaces and name prefixes may mitigate DoS attacks, however they come at the cost of quality of service degradation for legitimate clients. By preventing content caching through either tunneling or request flagging many privacy-focused schemes also inadvertently affect user QoE and QoS. For example, a privacy-sensitive client may unnecessarily mark all its content as private thus making caching ineffective. This will result in increased network load, and increased download latency for other users.

The architectures that use name based routing to route requests across the network (CCN, NDN, MobilityFirst) will fare better in the face of DoS/DDoS attacks on account of greater network-spread of interests and request aggregation; this is in contrast to architectures that route to specific set of nodes for efficiency (NetInf, PURSUIT) and hence adversely impact attack resilience. If end-to-end privacy by tunneling or other mechanisms are used, the network-wide routing approaches cannot benefit from in-network caching. At that point nothing separates the two architecture classes; the better the infrastructure the better the resilience.

The **second** lesson learned is that security concerns should be addressed at the intrinsic level. For example, content poisoning and cache pollution attacks are enabled due to lack of secure naming and caching schemes. We believe that these attacks should be solved intrinsically by employing strong cache verification mechanisms and self-certifying naming schemes, which would inherently eliminate unpopular content from the cache and prevent forged content from lingering in the network. Similarly, a scalable naming scheme would not only eliminate many opportunities for malicious behavior, but it also will improve the efficiency of content routing. We note that despite these issues in-network caching is becoming a preferred approach, especially at the network-edge, propelled by the rapid developments in 5G technologies. Architectures that enable pervasive caching will thus receive more and more attention.

Third, in ICN, the privacy risks emanate from the data interest traveling in plaintext in the network. In the era of widespread consumer profiling, in which data consumption information are invaluable to corporations, service providers, and censors, existing ICN architectures have a wide attack surface for data collection. Although a handful of proposed mechanisms try to achieve communication anonymity, they approaches have tended to port previous solutions from IP to the ICN paradigm. We believe more needs to be done to develop a mechanism, which can preserve privacy, while still leveraging the inherent ICN benefits. In this scenario, it is not very clear which class of architecture would perform the best for privacy; more research is needed to answer this question.

Fourth, the fundamental principles of ICN should be closely followed during the design of new security mechanisms. Here, we specifically refer to the necessity of efficient access control enforcement mechanisms that are in agreement with ICN principles. ICN, in principle, promotes content availability by allowing pervasive caching, and hence requires more advanced, *service-independent* access control mechanisms. In this survey, we have identified some initial attempts towards an independent access control mechanism that can be enforced by any network caching entities efficiently. Again, in this context it is not clear if there is a specific architecture that stands out as best for access control; but we note that all architectures are nascent and still under a lot of flux. We suggest the research community must keep ICN principles in mind, such that future access control schemes may protect content without undermining features necessary for the future mobile devices and 5G-enabled Internet, such as in-network caching and use of multiple radio technologies concurrently for communication.

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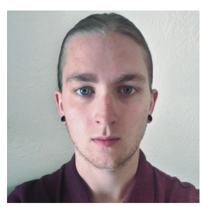

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