Elements of Trust in Named-Data Networking

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ABSTRACT
In contrast to today’s IP-based host-oriented Internet architecture, Content-Centric Networking (CCN) emphasizes content by making it directly addressable and routable. Named Data Networking (NDN) is an instance of CCN designed as a candidate next-generation Internet architecture. By opportunistically caching content within the network (in routers), NDN appears to be well-suited for large-scale content distribution and for meeting the needs of increasingly mobile and bandwidth-hungry applications that dominate today’s Internet.

One key feature of NDN is the requirement for each content object to be digitally signed by its producer. Thus, NDN should be, in principle, immune to distributing fake (aka “poisoned”) content. However, in practice, this poses two challenges for detecting fake content in NDN routers: (1) overhead due to signature verification and certificate chain traversal, and (2) lack of trust context, i.e., what public key(s) is/are trusted to verify which content. Due to these issues, NDN currently does not force routers to verify content signatures, which makes the architecture susceptible to content poisoning attacks.

This paper explores root causes of, and some cures for, content poisoning attacks in NDN. In the process, it becomes apparent that meaningful mitigation of content poisoning is contingent upon a trust management architecture, elements of which we construct while carefully justifying specific design choices. This work represents the initial effort towards comprehensive trust management for NDN.

1. INTRODUCTION
The Internet usage model has changed considerably over the last two decades. Limitations of the current Internet are becoming more pronounced as network services and applications become increasingly mobile and data-centric. In recent years, a number of research efforts have sprung up to design the next-generation Internet architecture. Some are based on the notion of Content-Centric Networking (CCN) which emphasizes efficient and scalable content distribution. Named Data Networking (NDN) is one such research effort. One of the main tenets of NDN is to name content, instead of communication end-points. It also stipulates in-network content caching, by routers. To secure each content, NDN requires it to be (cryptographically) signed by its producer. This way, globally addressable and routable content can be authenticated by anyone, which allows NDN to decouple trust in content from trust in entities that store and disseminate it. NDN entities that request content are called consumers. A consumer is expected to verify content signatures in order to assert:

- **Integrity** – a valid signature (computed over a content hash) guarantees that signed content is intact;
- **Origin Authentication** – since a signature is bound to the public key of the signer, anyone can verify whether content originates with its claimed producer;
- **Correctness** – since a signature binds content name to its payload, a consumer can securely determine whether delivered content corresponds to what was requested;

Although any entity can verify any content signature, NDN routers are allowed, yet not required, to do so. This is not only because of the overhead stemming from the actual cryptographic verification of the signature itself. There are two other, more important, reasons for not mandating router verification of content signatures:

1. First, a router must be aware of the specific trust model for each content-producing application. Although many applications use a similar hierarchical trust model, it is clear that they will not adhere to a uniform one. Some will use trust hierarchies, while others might adopt a flat peer-based trust model or hybrid versions thereof. Furthermore, NDN-supported applications are very likely to be a dynamic set – new ones will be added and older ones might be phased out. Also, a given application’s trust model might not be fixed.

2. Meanwhile, depending on the trust model of a given application associated with a particular content, a router needs access to (and thus might need to fetch) multiple public key certificates (or similar structures) in order to trust the public key that verifies a content signature. For example, if an application uses a hierarchical PKI, an entire root-to-leaf path might have to be traversed and all intermediate certificates would need to be separately verified. This would need to include ancillary activities for each such certificate, i.e., expiration and revocation checking.

These issues greatly complicate trust management in NDN routers. One easy alternative – adopted by the current version of NDN – is to make it optional for routers to verify content signatures. Unfortunately, this decision leaves NDN vulnerable to content poisoning attacks on router caches. To make matters worse, NDN does not provide any definitive mechanism for a consumer to request genuine desired content. Instead, a consumer that receives fake content can explicitly exclude the latter (by referring to its hash) in subsequent requests. This does not guarantee eventual success, due to the potentially unbounded number of fake content

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objects sharing the same name.

This undesirable state-of-affairs serves as the main motivation for our work. In this paper, we analyze the NDN architecture and its susceptibility to content poisoning attacks. Next, we postulate some intuitive goals for NDN routers to support trust management and content validation. We then present simple rules that allow all NDN parties (consumers, producers and routers) to mitigate content poisoning, while minimizing trust-related complexity for routers. These rules require no changes to the fundamentals of the NDN architecture.

Besides being the first effort to address content poisoning and trust management in NDN, one contribution of this work is in careful analysis and justifications for placement and complexity of various trust mechanisms.

**Scope:** as reflected by its title, this paper focuses on network-layer trust issues, motivated by the content poisoning problem. We do not address other NDN security issues, including interest flooding attacks, cache pollution attacks, routing security issues, as well as many others.

2. NDN OVERVIEW

Unlike IP which focuses on end-points of communication and their names/addresses, NDN [15][20] emphasizes content and makes it named, addressable and routable at the network layer. A content name is composed of one or more variable-length components opaque to the network. Component boundaries are explicitly delimited by “/” in the usual path-like representation. For example, the name of CNN home-page content for May 20, 2013 might be: /ndn/cnn/news/2013may20/index.htm. Large content can be split into segments with different names, e.g., fragment 37 of Alice’s YouTube video could be named: /ndn/youtube/alice/video-749.avi/37.

NDN communication adheres to the pull model and content is delivered to consumers only following an explicit request. There are two types of packets in NDN: interest and content. A consumer requests content by issuing an interest packet. If an entity can “satisfy” a given interest, it returns a corresponding content packet. Content delivery must be preceded by an interest. If content C with name n is received by a router with no pending interest for n, C is considered unsolicited and is discarded. Name matching in NDN is prefix-based. For example, an interest for /ndn/youtube/alice/video-749.avi can be satisfied by content named /ndn/youtube/alice/video-749.avi/37.

NDN content includes several fields. In this paper, we are only interested in the following:

- **Signature** – a public key signature, generated by the content producer, covering the entire content, including all explicit components of the name and a reference to the public key needed to verify it.
- **Name** – a sequence of explicit name components followed by an implicit digest (hash) component of the content that is recomputed at every hop. This effectively provides each content with a unique name and guarantees a match with a name provided in an interest. However, in most cases, the hash component is not present in interest packets, since NDN does not provide any secure mechanism to learn a content hash a priori.
- **PublisherPublicKeyDigest (PPKD)** – an SHA-256 digest of the public key needed to verify the content signature.
- **Type** – content type, e.g., data, encrypted content, key, etc.
- **Freshness** – a recommendation of the lifetime of the content in the cache.
- **KeyLocator** – a reference to the public key required to verify the signature. This field has three options: (1) verification key, (2) certificate containing the verification key, or (3) NDN name referencing the content that contains the verification key.
- **Exclude** – a recommendation of the lifetime of the content in the cache.

Each content producer is required to have at least one public key, represented as a *bona fide* named content of Type= key, signed by its issuer, e.g., a certification authority (CA). The name of a public key content object must contain “key” as its last explicit component, e.g., /ndn/russia/moscow-airport/transit/snowden/key.

An NDN interest includes the following fields:

- **Name** – NDN name of requested content.
- **Exclude** – contains information about name components that must not occur in the name of returned content. This field can also be used to exclude certain content by referring to its hash, which, as noted above, is considered to be an implicit, last component of each content name.
- **PublisherPublicKeyDigest (PPKD)** – the SHA-256 digest of the publisher public key. If this field is present in the interest, a matching content objects must have the same digest in its PPKD.

There are three types of NDN entities:

- **(1) consumer** – an entity that issues an interest for content.
- **(2) producer** – an entity that produces and publishes (as well as signs) content, and
- **(3) router** – an entity that routes interest packets and forwards corresponding content packets. Each entity (not just routers) maintains the following three components:

  - **Content Store (CS)** – cache used for content caching and retrieval. From here on, we use the terms CS and cache interchangeably. Recall that a recommended time to cache each content is specified in the freshness field.
  - **Forwarding Interest Base (FIB)** – routing table of name prefixes and corresponding outgoing interfaces used to route interests. NDN does not specify or mandate any routing protocol. Forwarding is done via longest-prefix match on names.
  - **Pending Interest Table (PIT)** – table of outstanding (pending) interests and a set of corresponding incoming and outgoing interfaces.

When a router receives an interest for content named n (which is not in its cache), and there are no pending interests for the same name in its PIT, it forwards the interest to the next hop(s), according to its FIB. For each forwarded interest, a router stores some amount of state information, including the name in the interest and the interface on which it arrived. However, if an interest for n arrives while there is already an entry for the same content name in the PIT, the router collapses the present interest (and

2Recall that NDN is agnostic as far as trust management, aiming to accommodate peer-based, hierarchical and hybrid PKI approaches.

3Note that a physical entity (a host, in today’s parlance) can be both consumer and producer of content.
any subsequent interests for n) storing only the interface on which it was received. If and when content is returned, the router forwards it out on all incoming-interest interfaces and flushes the corresponding PIT entry. Since no additional information is needed to deliver content, an interest does not carry any source address. (If a content fails to arrive before some router-determined expiration time, the router can either flush the PIT entry or attempt interest retransmission over the same or different interfaces.)

An NDN router’s cache size is determined by local resource availability. Each router unilaterally determines which content to cache and for how long. Upon receiving an interest, a router first checks its cache to see if it can satisfy the interest locally. Therefore, NDN in general (and interests, in particular) lacks any notion of a destination address, since cached content can be fetched from any NDN entity. Producer-originated content signatures allow consumers and routers to authenticate received content, regardless of the entity serving it. As mentioned earlier, content signature verification is mandatory for consumers and optional for routers.  

3. CONTENT POISONING

NDN’s key design objective is efficient and scalable distribution of content. This is facilitated by routers opportunistically caching content. Whenever an NDN router receives an interest for a name that matches some content in its cache, it satisfies the interest with that content. Since routers are not required to verify signatures, the delivered content is not guaranteed to be authentic. However, a consumer is required to verify signatures of all returned content. A consumer is thus assumed to have the necessary application-specific trust context to decide which public keys to trust. This allows consumers to reliably detect fake content.

However, NDN offers no means for consumers to ask routers to flush fake content from their caches. The only recourse for a consumer that detects fake content is to issue another new interest that specifically excludes the unwanted content by specifying its hash in the exclusion filter field of the new interest. Unfortunately, this explicit exclusion does not signify (to the routers) bad or poisoned content – it can also be used to exclude stale content. Furthermore, even if the exclusion technique were to be used strictly for flagging poisoned content, the result would be undesirable, for the following reasons:

The entire notion of consumers (i.e, end-systems or hosts) informing routers about poisoned content is full of pitfalls. Suppose a consumer complains to a router about specific content. If this is done without consumer authentication (whether via an interest, e.g., using exclusion, or via a separate packet type), the router would have two choices: (1) immediately flush referenced content from its cache, or (2) verify the content signature and flush content only if verification fails. The former (1) is problematic, since it opens the door for anyone to cause easy removal of popular content from router caches, which can be considered as a type of a denial-of-service attack. Even if this were not an issue, there would remain a more general problem: as noted in [13], the adversary mounting a content poisoning attack could continue ad infinitum to feed new invalid content in response to interests that exclude previously consumer-detected invalid content. The second option (2) is also problematic, because, besides the cost of verifying a signature (which can lead to a denial-of-service attack), it brings back the problem of routers having to understand potentially complex trust semantics of many diverse content-producing applications.

Another possibility is to require consumers to authenticate themselves when complaining about poisoned content. This would entail signing the interest (or another new packet type) that complains about allegedly bad content. One unpleasant privacy consequence is that the signer (consumer) would be exposed by the signature, since it would need to be bound to a public key, contained in a certificate. (This certificate would have to be communicated along with each complaint message, and auxiliary information that the router would need to trust the certificate.) More generally, signing would violate one of the key elements of NDN architecture – consumer opacity. Recall that producers sign content while consumers do not sign interests, or any other messages.

Another reason why consumer signing of “complaint” messages is a bad idea is because it can be abused to mount DoS attacks on routers by flooding them with junk complaints and forcing expensive signature verification.  

Note that, even if the router successfully authenticates a consumer complaint, this is no guarantee that the accused content is fake; in order to be sure, the router would have to verify the content signature as well. Moreover, authentication of consumers by routers would require identity management and verification systems to be in place at the network layer, thus adding significant overhead.

Finally, the preceding discussion applies not only for content cached by routers. Since NDN only recommends, and does not mandate, content caching, it is entirely legal for a router not to cache some, or all, content it forwards. If a router does not cache C, then complaining about C being fake is clearly useless.

At this point, it becomes clear that dealing with fake content represents a challenge for the NDN architecture. Although some light-weight non-cryptographic and partially effective counter-measures have been proposed (e.g., [14]), they do not fully address the problem. In the remainder of this paper we show that content poisoning is indeed a very real issue. Next, we postulate some simple rules that pave the way towards the elements of network-layer trust management for NDN.

3.1 Zooming In

Based on the above arguments and recent results simulating content-poisoning attacks [14], we conclude that NDN has a major problem, since it offers: (1) no way to prevent fake content from being delivered to consumers, and (2) no way to reliably flush invalid content from router caches. There are two reasons for this problem:

1. Ambiguous interests: NDN requires each interest to carry the name of desired content. However, neither the implicit hash component of the name, nor the PPKD is a required field in an interest. In other words, an interest for a content name can be satisfied by multiple content objects, including those with untrusted or unverifiable signatures.

2. No unified trust model: even if routers could verify signatures at line speed, NDN does not provide a trust model
enforceable at the network layer. Although two aforementioned selector fields can be used to communicate content-specific trust context to the network layer, NDN has no mechanism for a consumer to securely pre-acquire the hash of a given content, or the specific public key that should be used to verify a content signature.

In order to demonstrate the grave effect content poisoning can have on NDN, we conducted a simple experiment using ndnSIM \([3]\) – a simplified implementation of NDN architecture as a NS-3 \([21]\) module. Our results verified that content poisoning can significantly delay or block customers from accessing valid content. Details about the experiment setup and results can be found in Appendix A.

3.2 Goals
As a first step in addressing the content poisoning problem, it is necessary to recognize the obvious, i.e., that network-layer trust management and content poisoning are inseparably tied to each other. Since content is the basic unit of network-layer “currency” in NDN, trust in content (and not in its producers or consumers) is the central issue at the network layer.

Second, trust-related complexity (activities, state maintenance, etc.) must be minimized at the network layer. Specifically, as part of establishing validity of content, a router should not: fetch public key certificates, perform expiration and revocation checking of certificates, maintain its own collection of certificates, or be aware of trust semantics of various applications. On a related note, a router should verify at most one signature per content. This upper-bounds the heavier part of content-related cryptographic overhead; the other part is computing a content hash. Ideally, a router would not perform any signature verification at all. However, as discussed below, this might be possible for some, yet not all, content. Also, although verifying a signature given an appropriate public key is a mechanical operation, a router would still need to support multiple signature algorithms as it is improbable that all applications would adopt the same signature algorithm.

The above discussion implies that NDN entities other than routers, i.e., producers and consumers of content, should bear the brunt of trust management.

4. THE INTEREST-KEY BINDING RULE
Our approach to network-layer trust – that adheres to all desired goals outlined above – is based on one simple rule, that we denote as Interest-Key Binding (IKB):

IKB: An interest must reflect the public key of the producer.

Recall that NDN interest format (Section 2) includes an optional field PPKD which serves exactly this purpose. Our approach makes it mandatory without any substantive changes to the NDN architecture. The only exception to IKB could be the use of interests that carry self-certifying names; see Section 5.

An NDN public key is a special type of content in the form of a certificate signed by the issuing CA. Each certificate contains a list of all name prefixes that it is authorized to sign/verify. The name of the certificate-issuing (content-signing) CA and the name of the key contained in a certificate (content) are not required to have any common prefix. This is part and parcel of NDN’s philosophy of leaving trust management up to the application, e.g., signed content \(C\) can be verified with public key \(PK\) with \(C\) and \(PK\) having no common prefix requirement. For instance, content containing the public key /\(cn\)/\(usa\)/\(web\)/\(key\) could be issued and verified by the key /\(verisign\)/\(key\). Of course, an application is free to impose all kinds of restrictions, as long as routers remain oblivious.

4.1 Implications for Producers and Routers
We now examine the implications of IKB on content producers and routers, respectively.

For content producers, IKB has very few consequences. In particular, it simplifies construction of content by asking a producer to include the public key itself in the KeyLocator field of content. In other words, IKB obviates two other current NDN options of (1) referring to a verification key (from the content KeyLocator field) by its name, or (2) including it in a form of a certificate. The only exception to this rule are content objects that would always be requested by consumers using self-certifying names (such as content distributed via secure catalogs as described in Section 5), where no key information is necessary.

For routers, the implications of IKB are overwhelmingly positive due to the simplification. First, a router needs to perform no fetching, storing or parsing of public key certificates, as well as no revocation or expiration checking. All such activities are left to consumers.

Upon receiving a content and identifying its corresponding PIT entry (corresponding to one or more pending interests) a router simply hashes the public key from the content KeyLocator field and checks whether it matches the PPKD of the PIT entry. In case of a mismatch, the content is discarded. In a somewhat simpler realization, we can imagine that, for each incoming content PIT lookup is done by using both content name and public key hash. In case of a match, the content signature is verified and, if found valid, the content is forwarded and optionally cached.

4.2 Implications for Consumers
For consumers, IKB does not increase complexity; it only forces them to codify desired consumer behavior – something that has been left unspecified (on purpose) in the NDN architecture.

The most immediate IKB consequence for a consumer is the need to obtain and validate the producer’s public key before issuing an interest for any content originated by that producer. At the first glance, this might appear to be an example of the proverbial “chicken-and-egg” problem. However, we show below that this is not the case.

A consumer that wants to fetch certain content \(C\) is doing so as part of some NDN application, \(APP_c\). We assume that a consumer must have already installed this application. \(APP_c\) must have a well-defined trust management architecture that is handled by its consumer-side software. However, the remaining question is: how to bootstrap trust and how to obtain initial public keys?

We consider three non-exclusive alternatives:

(1) One possibility is that \(APP_c\) client-side software comes with some pre-installed root public key(s), perhaps contained within self-signed certificates. Without loss of generality, we assume that there is only one such key – \(PK_{root}\).
Armed with it, a consumer can request lower-level certificates, by issuing an interest referencing the hash of $PK_{root}$ in the PPKD field.\(^7\)

(2) Alternatively, we could envision a global NDN Key Name Service (KNS), somewhat akin to today’s Domain Name Service (DNS). In response to consumer-issued special interests referencing public key names (and/or name prefixes), KNS would reply with signed content that would contain one or more public key certificates (i.e., embedded content) corresponding to requested names.

(3) Another similar possibility is to imagine a global search-based service, i.e., something resembling today’s Google. A consumer would issue a search query (via an interest) to the search engine which would reply with signed content representing a set (e.g., one page at a time) of query results. One or more of those results would point to content corresponding to the public key certificate of interest to the consumer.

In cases (2) and (3), consumers would still need to somehow securely obtain the root public keys for KNS and the search engine, respectively. This can be easily done via (1).

### 4.3 Security Arguments

We now return to the original motivation for this work – mitigation of content poisoning attacks. We need to show that global adherence to the IKB rule leads to security against content poisoning.\(^7\)

If we assume that, in addition to all entities adhering to IKB:

1. The consumer requesting content $C$ is not malicious.
2. Each router $R$ that is one hop away from (adjacent to) the consumer is not compromised.
3. The links between a consumer and all adjacent routers are not compromised.

We can briefly argue security by contradiction: Suppose that a consumer receives some fake content $C$ from $R$. Let $Int$ denote the interest (issued earlier by that consumer) that was satisfied by $C$. According to IKB, $Int$ must contain the digest of a public key of producer $P$ in its PPKD field. Let $PK$ denote this public key. Consequently, $R$ must have made sure that: (1) $C$ is signed with a public key $PK'$ with a hash matching PPKD of $Int$, meaning that $H(PK') = H(PK)$ and (2) the signature itself is correct, i.e., valid. Also, since $R$ is not malicious and all communication between $R$ and the (also not malicious) consumer is secure, the only remaining possibility is a hash collision, i.e., $PK' \neq PK$ while $H(PK') = H(PK)$. The latter is assumed to occur with negligible probability.

This does not yet conclude our security discussion. As noted in \(^{13}\), content poisoning attacks can originate with malicious routers. What happens if a malicious router $R'$ feeds poisoned content $C'$ to its non-malicious next hop neighbor $R$, towards some consumer($s$)? Since $R$ is honest and implements IKB, before forwarding and (optionally) caching $C'$, it verifies, as before, that the signature of $C'$ is successfully verifiable using $PK$ that matches the hash in the corresponding PIT entry, i.e., the value of the PPKD field of the original interest $Int$ that triggered creation of this PIT entry.

A more detailed security argument is provided in Appendix B.

### 5. OPTIMIZATIONS

As mentioned before, IKB implies that routers should perform only one signature verification using the public key provided (by the producer) in the content and specified (by the consumer) using the PPKD field in the interest. Instead of including the public key in the content, it could be directly included by the consumer in the interest. This would require storing the key alongside the interest in the PIT entry, to be used later for signature verification of the content. Since it is fair to assume that cache entries have longer lifetime than PIT entries, this approach can be beneficial in terms of storage. Its main drawback, however, is that the current interest format would need to be modified to include public keys.

For backbone routers that process and forward tens of gigabits per second, performing even a single signature verification per packet imposes a huge overhead. One approach to overcome this problem is to take advantage of the network structure. The current Internet is divided into Autonomous Systems (AS-\'s), each representing an administrative entity. In this architecture, only border routers of consumer-facing AS-\'s might implement the IKB rule by verifying signatures of all received contents. Alternatively, each router in an AS could probabilistically verify packet signatures. The main drawback of these approaches is that fake content could still be cached by routers that did not verify its signature. However, either method would have good chance of detecting and discarding most fake content before reaching to the consumer.

An alternative for reducing signature verification overhead is the use of self-certifying content names \(^{13}\) 4. As mentioned in Section 2 a hash of requested content can be provided as the last component of a name in an interest, thus forming a self-certifying name. If a benign consumer uses such names, the network guarantees (due to longest-prefix matching) delivery of “valid” content. The advantage of using self-certifying names is that routers would no longer need to verify signatures. Instead they would only recompute the content hash and check that it matches the one in the corresponding PIT entry. The remaining question is: how would a consumer obtain the hash of a content beforehand?

For this purpose, we propose the use of catalogs. Technically, a catalog is an “authenticate-able” data structure providing a list of self-certifying names. This list consists of references to content objects containing data, public keys, or even other catalogs. The structure of catalogs could be application-specific and can vary from a single a list of self-certifying names, to several lists in different content objects forming a Merkle tree \(^{19}\). For securely fetching catalogs, consumers can use the PPKD field of the interest, as discussed in Section 4.

One corollary of using self-certifying names in interest messages is that consumers and routers are no longer required to verify a content signature, as long as the self-certifying name is trusted, i.e., obtained using a catalog. This reduces: (1) overhead of publishing new content, since producers do not need to sign it, and (2) network overhead, since there is no need to add the public key to the KeyLocator field of the content, as discussed in Section 4.
The only time a signature is required is if a content is requested by specifying the PPKD field of the interest. In that case, routers (prior to serving from cache or forwarding) and consumers (prior to accepting) must verify the content’s signature. It is up to the producer to decide whether a content should be requested by specifying its corresponding public key, using a self-certifying name, or even both.

6. PROPOSED MODEL IN PRACTICE

The goal of designing and implementing a new Internet architecture, such as NDN, is to have a replacement candidate for the current IP-based network. In order for this migration to be smooth and successful, NDN should be able to adapt to application specific requirements, such as trust. In this section we discuss how the aforementioned trust model and its optimizations could be applied in practice. We start by identifying different NDN traffic types.

6.1 Content Distribution

This type of traffic corresponds to client-server communication in today’s network, where many clients are requesting content from few servers. Since most requested content is static, creating catalogs is straightforward. For their part, consumers request catalogs and then use included self-certifying names to request desired content. We consider two common examples of content distribution traffic:

- **Video Streaming**: A typical video is a large content split into several segments with different names (as mentioned in Section 2). If a catalog containing the self-certifying names of all the segments can be provided, consumers can use these names in subsequent interests to retrieve all segments of the video.

- **Internet Browsing**: We anticipate that most HTML files would fit into a single content [23, 1]. A typical HTML file contains reference links to other static and dynamic content, such as images, audio or other HTML pages (sub-pages). While rendering HTML files, Internet browsers parse all reference links and download corresponding content. Therefore, if an HTML file uses self-certifying names as references, it can be viewed and treated as a secure catalog. Of course, self-certifying names can only be used for static content, since the hash of dynamic (e.g., generated upon request) content cannot be known a priori.

Internet browsing provides a good example of content that can be requested by either IKB or via self-certifying names. Suppose that a web page A contains a reference link to sub-page B and this link is expressed using a self-certifying name. Once a consumer requests and obtains page A, the client browser can request B using the self-certifying name within A. Whereas, other consumers might wish to directly request page B (not as part of A) using its producer’s public key digest.

However, it is not clear how self-certifying names can be applied in case of web pages forming a loop, e.g., page A has a link to page B, and page B has a link to page A.

6.2 Interactive Traffic

The second type of traffic in NDN is interactive communication where content is generated on demand. All traffic generated by applications such as voice and video calls, SSH sessions, and gaming fit into this category. Such applications benefits from caching only in case of packet loss, where re-issued interests for retransmission are (likely) satisfied from the first hop router. This reduces latency and improves quality of service. Since interactive traffic is generated at run-time, building big catalogs in advance might not be feasible. Instead, consumers should request content by specifying the PPKD field in interest messages or dynamically generated small catalogs can be utilized if small delays are tolerable.

7. RELATED WORK

Prior work on Denial of Service (DoS) attacks in NDN includes [8] and [2]. Both results addressed a specific DoS attack type based on flooding routers with interest messages. Content poisoning was identified in [13] which also outlines some tentative countermeasures. Subsequently, [14] proposed the first concrete countermeasure based on analyzing exclusion patterns for cached content to determine whether it is fake.

Trust and trust management systems are well studied in the literature, especially, in distributed environments, such as MANETs, ad hoc and wireless sensor networks (WSNs). [7] surveys the state of the art in trust management systems for MANETs. It emphasizes the need to combine the notions of “social trust” with “quality-of-service (QoS) trust”. A similar survey can be found in [22].

[18] presents an extensive review of trust management systems in WSNs. Based on unique features of WSNs, trust management system’s best practices are derived and state of the art countermeasures are evaluated against them. [25] discusses security challenges in designing WSNs. It distinguishes between the definitions of trust and security, and shows that cryptography is not always the solution for trust management. Instead, techniques from other domains should be included in defining and formalizing trust.

Since a single trust metric might not suffice to express trustworthiness of nodes, a multi-dimensional trust management framework is suggested in [17]. Three metrics are used: (1) node collaboration to perform tasks, such as packet forwarding, (2) node behavior, e.g., flagging nodes that flood the network, and (3) correctness of node-disseminated information, e.g., routing updates.

[9] proposes a framework for calculating a network entity’s reputation score based on previous interactions feedback. In this framework, each service can apply its own reputation scoring functions. It also supports caching of trust evaluation to reduce network overhead, and provides an API for reporting feedback and calculating reputation scores.

Policymaker [5] is a tool that provides privacy and authenticity for network services. It offers a flexible and unified language for expressing policies and relationships. It also includes a local (per site or network) engine for carrying all trust operations, such as granting access to services.

All aforementioned techniques involve keeping track of other nodes’ behavior in order to decide whether they are trusted. However, this general strategy is a poor match for NDN, since routers need an efficient mechanism to trust content, and not other entities. Because content can be served from anywhere it is impractical for routers to trust other entities.
8. CONCLUSIONS

As argued in this paper, the NDN architecture is inherently susceptible to content poisoning attacks. We postulated some intuitive trust management goals needed to support content validation in NDN routers. To mitigate content poisoning attacks, we presented simple rules that allow all NDN nodes to determine whether received content is valid. These rules require no changes to NDN architecture tenets. We also presented some overhead-lowering optimization techniques.

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APPENDIX A

We first describe the adversary model and how fake content can be injected. We consider a proactive content poisoning attack whereby Adv anticipates interests for content C with name n and injects fake content with the same name into router caches. Fake content can be injected into the network via malicious routers or end-nodes. For example, consider an Adv consisting of malicious consumer Cr_m and a malicious producer P_n targeting a specific victim router R_v. Assuming that Cr_m and P_n are connected to different interfaces of R_v, Cr_m sends an interest for n. Once this interest is received by R_v and an entry is added to the PIT, P_n sends a fake content to R_v which is promptly cached. Consequently, R_v is pre-polluted with fake content, ready for arrival of genuine interests. To maximize longevity of the attack, P_n sets the freshness field of fake content to a maximum value.
We simulate the DFN topology. Deutsches ForschungsNetz (German Research Network) – a network developed for research and education purposes. It consists of several connected routers positioned in different areas of the country, as shown in Figure 1(a). Our experiment measures how many benign consumers can retrieve a satisfactory (genuine) content and how fast they can do so when the router caches are poisoned. The simulation starts with core router caches pre-populated with various fake versions of the target content, 80% (1 valid and 4 fake content objects), 90% (1 valid 9 fake objects), 99% (1 valid 99 fake objects), and 99.9% (1 valid 999 fake objects). To show the effect of having multiple consumers connected to the same router, we configure edge router to run without cache. Figure 1(b) shows the results of this experiment. We can notice that it takes more than 20 seconds for 90% of the consumers to retrieve valid content in the case pre-populated fake content objects rate of 99%. Moreover, more than 60% of the consumers do not receive valid content during the time of the simulation, when the pre-population rate is 99.9%.

APPENDIX B

Definition 9.1. A hash function \( \mathcal{H} \) is second pre-image resistant, if for any given \( x \), no probabilistic polynomial-time (PPT) adversary \( A \) can find a value \( x' \neq x \) such that \( \mathcal{H}(x) = \mathcal{H}(x') \). In other words, \( \Pr [ \mathcal{H}(x) = \mathcal{H}(x') ] \leq \epsilon(n) \), where \( \epsilon(n) \) is negligible and \( n \) is the security parameter.

A formal definition of probabilistic polynomial-time adversaries and negligible functions can be found in [10].

Definition 9.2. A signature scheme \( \Pi \) is unforgeable if for any message \( m \), no PPT adversary \( A \) (given a public key \( PK \)) can generate a valid signature without knowing the corresponding private key. We denote the success of \( A \) as \( A^{\text{forge}}(m) = 1 \), i.e., if \( \Pi \) is unforgeable, there exists a negligible function \( \epsilon(n) \) such that: \( \Pr [ A^{\text{forge}}(m) = 1 ] \leq \epsilon(n) \).

Definition 9.3. For any interest message \( \text{Int} \) with \( \mathcal{H}(PK) \) (the digest of the verifying public key for the corresponding content) assigned to the PPKD field, and for any \( \mathcal{A} \), the NDN cache poisoning experiment is defined as follows:

Given \( \text{Int} \) as input to \( \mathcal{A} \), it outputs a content object \( C' \) containing: (1) a public key \( PK' \) in the KeyLocator field, (2) a digest of this key \( \mathcal{H}(PK') \) in PPKD, and (3) a signature \( \sigma' \) in the Signature field. The output of this experiment is defined to be 1 if one of the following holds:

- \( PK \neq PK' \) and \( \mathcal{H}(PK) = \mathcal{H}(PK') \),
- or, \( PK = PK' \) and \( \sigma \) is valid.

In other words, \( \mathcal{A} \) can either violate the second pre-image resistance of \( \mathcal{H} \) (we denote this event as collision which occurs with some probability \( p_f \) and succeeds with \( \Pr [ \mathcal{H}(x) = \mathcal{H}(x') ] \)), or forge the signature (we denote this event as forge which occurs with some probability \( p_f \) and succeeds with \( \Pr [ A^{\text{forge}}(m) = 1 ] \)). We denote the success of \( \mathcal{A} \) as \( \mathcal{A}^{\text{ppkd}}(\text{Int}) = 1 \).

Theorem 9.4. Given \( \mathcal{H}, \Pi \) (as defined above), \( \mathcal{A} \) succeeds in injecting a fake content object \( C' \) into a network that abides by the IKB rule with a negligible probability \( \epsilon(n) \).

\[ \Pr [ \mathcal{A}^{\text{ppkd}}(\text{Int}) = 1 ] \leq \epsilon(n) \]

Proof. We show the above by contradiction:

Assume that \( \mathcal{A} \) succeeds in injecting \( C' \) with a non-negligible probability. Then, we can construct a reduction \( \mathcal{A}' \) (another PPT adversary), that uses \( \mathcal{A} \) to break second pre-image resistance of \( \mathcal{H} \), or unforgeability of \( \Pi \):

Adversary \( \mathcal{A}' \)
1. Is given a hash value \( x \).
2. Creates an interest message \( \text{Int} \) and sets \( \mathcal{H}(x) \) as its PPKD field value.
3. Runs \( \mathcal{A}(\text{Int}) \) to obtain \( C' \).
4. Extracts from \( C' \) and outputs:
   - (a) \( PK' \) as a collision with \( x \), if \( x \neq PK' \),
   - (b) or \( \sigma' \) as a forged signature for \( C' \), if \( x = PK' \).

We now determine the probability of success of \( \mathcal{A}' \). Whenever either collision or forge event occurs \( \mathcal{A}' \) succeeds.
Therefore,

$$\Pr[\text{A' succeeds}] = \Pr[\text{collision } \cup \text{ forge}]$$

$$= p_c \cdot \Pr[H(x) = H(PK')]$$

$$+ p_f \cdot \Pr[A'_{\text{forge}}(C') = 1]$$

$$> \epsilon(n)$$

The last inequality holds because A’ succeeds with the same probability as A, which is non-negligible. If the result of adding two functions is non-negligible, at least one of them must be non-negligible [16]. Moreover, since both $p_c$ and $p_f$ cannot be exponential functions, then either

$$\Pr[H(x) = H(PK')] > \epsilon(n)$$

or

$$\Pr[A'_{\text{forge}}(C') = 1] > \epsilon(n).$$