Security and Privacy Analysis of NSF Future Internet Architectures

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Abstract—The Internet Protocol (IP) is the lifeblood of the modern Internet. Its simplicity and universality have fueled the unprecedented and lasting global success of the current Internet. Nonetheless, some limitations of IP have been emerging in recent years. Its original design envisaged supporting perhaps tens of thousands of static hosts operating in a friendly academic-like setting, mainly in order to facilitate email communication and remote access to scarce computing resources. At present IP interconnects billions of static and mobile devices (ranging from supercomputers to IoT gadgets) with a large and dynamic set of popular applications. Starting in mid-1990s, the advent of mobility, wirelessness and the web substantially shifted Internet usage and communication paradigms. This accentuated long-term concerns about the current Internet architecture and prompted interest in alternative designs.

The U.S. National Science Foundation (NSF) has been one of the key supporters of efforts to design a set of candidate next-generation Internet architectures. As a prominent design requirement, NSF emphasized “security and privacy by design” in order to avoid the long and unhappy history of incremental patching and retrofitting that characterizes the current Internet architecture. To this end, as a result of a competitive process, four prominent research projects were funded by the NSF in 2010: Nebula, Named-Data Networking (NDN), MobilityFirst (MF), and eXpressive Internet Architecture (XIA). This paper provides a comprehensive and neutral analysis of salient security and privacy features (and issues) in these NSF-funded Future Internet Architectures. It also compares the four candidate designs with the current IP-based architecture and discusses similarities, differences, and possible improvements.

Index Terms—network security, privacy, trust, future internet architectures

I. INTRODUCTION

The original Internet was intended to support thousands of users, mainly in North America, accessing shared resources via dumb terminals. Nowadays, the Internet connects over 3 billion of mobile and desktop devices with a variety of applications ranging from simple web browsing to video conferencing and content distribution. These extreme changes in Internet usage accentuated limitations of the current IP-based architecture and prompted research into alternative internetworking architectures.

In 2010, the National Science Foundation (NSF) launched its “Future Internet Architecture” (FIA) program [1]. Originally, FIA was a 5-year program with the goal of designing a set of candidate next-generation Internet architectures. In 2015, NSF renewed its commitment with a follow-on “Future Internet Architecture – Next Phase” (FIA-NP) program. Unlike FIA which focused on architectural research, FIA-NP emphasizes evaluation, via prototypes, testbeds, trial deployments, and extensive experimentation.

FIA originally included four research projects: Nebula [2, 3], Named-Data Networking (NDN) [4], MobilityFirst (MF) [5], and eXpressive Internet Architecture (XIA) [6]. Each project focuses on a new Internet architecture with a distinct vision and design principles. Nebula envisions a highly-available and extensible core network interconnecting numerous data centers that enable new means of distributed communication and computing. NDN focuses on scalable and efficient data distribution – thus addressing inadequacies of the current Internet’s host-centric design – by naming data instead of its location. MobilityFirst concentrates on scalable and ubiquitous mobility and wireless connections. Meanwhile, XIA stresses flexibility and addresses the need to support different communication models by creating a single network that offers inherent support for communication between various principals (including hosts, content and services) while remaining extensible to future ones. Only three of the original four FIA architectures were selected for continued funding under FIA-NP: NDN, MobilityFirst and XIA. Figure 1 illustrates the timeline of each project in FIA and FIA-NP programs.

![Timeline of FIA & FIA-NP programs](image)

Fig. 1. Timeline of FIA & FIA-NP programs

From the very beginning, one of FIA’s key goals (and requirements) is strong support for security and privacy in all future Internet architectures. Given the rocky history of security and privacy in the current Internet, this goal is both very sensible and extremely important.

In this paper, we survey and evaluate security and privacy features in aforementioned four FIA projects. In doing so, we consider the network layer of the current Internet architecture as a point of reference. We also show how each FIA architecture succeeds, exceeds or fails with respect to security and
privacy features of current Internet’s network layer, i.e., Internet Protocol (IP) and IP Security Extensions (IPSec). We also discuss potential vulnerabilities that can be exploited to attack transmission channels, end-nodes, and the network infrastructure. Since different types of resolution services are needed in all FIA architectures, we compare such security and privacy features of such services to those of Domain Name System (DNS) and DNS Security Extensions (DNSSEC).

To the best of our knowledge, this paper represents the first comprehensive security and privacy treatment of four FIA architectures. Since it is impossible to predict which FIA architecture(s), if any, will ultimately succeed, we strive to remain neutral, i.e., to provide a complete and fair analysis of security and privacy of these architectures.

Prior FIA surveys. An early article by Pan et al. provides a general overview and does not dwell on security and privacy aspects. The work in provides a security analysis of the four NSF-founded FIA architectures, plus Recursive InterNetwork Architecture (RINA), Service Oriented Network Architecture (SONATE), and Netlet-based Node Architecture (NENA). The analysis in considers four security features: confidentiality, integrity, availability, and authentication. Our work focuses on the four NSF-funded FIA architectures, with the aim of providing a more detailed investigation and comparison of a larger set of security features. Furthermore, different from , we analyze the security of NSF-funded FIA architecture resolution services.

Other surveys in the literature that focus on ICN architectures. Also, analyzed security and privacy of NDN without comparison with the current Internet architecture. investigates denial of service attacks in NDN, and provide a more complete analysis of security in various ICN architectures. It focuses on various attacks: Naming Related Attacks, Routing Related Attacks, Caching Related Attacks and Miscellaneous attacks. Instead, distinguishes between security, privacy and access control in ICN.

Other surveys in the literature that focus on ICN architectures do not primarily focus on security and privacy aspects. analyzes Data-Oriented Network Architecture (DONA), Named Data networking, Publish-Subscribe Internet Routing Paradigm (PSIRP) and Network of Information (NetInf). It focuses on naming, routing and forwarding, and caching and mobility. Moreover, marginally considers security and privacy aspects. Bari et al. compare the different naming and routing scheme adopted by DONA, NetInf, PURSUIT and PSIRP architectures.

None of discusses security and privacy features.

Organization. We begin by overviewing IP, IPsec, DNS and DNSSEC in Section. Next, sections through summarize Nebula, NDN, MobilityFirst and XIA, respectively. Section evaluates security and privacy features of these architectures, and compares them with those of IP and IPsec. Section analyzes security and privacy of resolution services used by each new architecture. Section summarizes our comparative analysis, and highlights open issues, and possible future research directions. Finally, Section concludes our paper.

II. THE INTERNET OF TODAY

Today’s Internet architecture was designed over three decades ago to seamlessly inter-connect multiple heterogeneous networks. At the core of today’s Internet is the TCP/IP protocol suite, which puts together protocols, applications and network mediums, and organizes them into four abstraction layers: Link, Internet, Transport and Application. This design leads to an hourglass shape with IP as the network layer as its “thin waist”.

We consider IP, which operates at the Internet layer, to be our point of reference when analyzing security and privacy of FIA architectures. IP is responsible for forwarding packets (a.k.a. datagrams) from the source IP interface to its destination counterpart. A host may have one or more IP interfaces, while a router has at least two. Each IP interface is identified by a distinct fixed-length IP address.

Another fundamental component of today’s Internet architecture, and subject of our analysis, is DNS. DNS is a distributed service that translates application-specific domain names (specified in URLs) into their corresponding IP addresses, allowing hosts to communicate using meaningful names, rather than IP addresses.

In what follows, we briefly describe IP and DNS.

A. Internet Protocol

The cornerstone of IP is addressing of network devices. Every network-layer entity (router or host) is identified by at least one IP address which consists of a network prefix and a host identifier. The boundary between them is flexible, which allows IP addressing to scale.

An IP datagram contains source and destination addresses along with other fields that convey control information. Actual data is carried in the payload field. When a packet is received, a router searches its Forwarding Information Base (FIB) to identify the next hop for that packet. A FIB contains a set of entries, each mapping one or more network prefixes to a router’s interface and a next-hop IP address. This allows routers to perform longest-prefix matching on the destination address to identify the next hop. If a packet can not be forwarded, it is dropped and an error message is generated via the Internet Control Message Protocol (ICMP). One important IPv4 feature is packet fragmentation. If the size of an IP packet is larger than the forwarding interface’s Maximum Transmission Unit (MTU), the packet must be divided into smaller chunks, called fragments. A destination host must reassemble fragments to recover the original packet. Other network entities, such as Network Address Translation

1ICMP is also used for sending control messages, such as routing redirect for networks and hosts.
tables (NATs) and firewalls might also assemble fragments.

As mentioned earlier, IP was originally designed for a small and relatively amicable research community. Neither its longevity nor its popularity was foreseen. Thus, it is unsurprising that IP lacks any security and privacy features. In late 1980-s and early 1990-s, as IP started to gain global popularity and the Internet transcended into the commercial sector, IPsec suite was designed to provide basic security services, such as: origin authentication, data integrity, and confidentiality for IP datagrams. The first two are attained via Authentication Header (AH) protocol, while Encapsulation Security Payload (ESP) protocol provides all three security features. IPsec supports two modes of operation:

- **Transport**: provides end-to-end communication, e.g., client-server communications. Only packet payloads are encrypted and authenticated in transport mode. Transport and application layers of packets are secured by a hash, thus, they can not be modified, e.g., using NAT. NAT-Traversal (NAT-T) is developed to overcome this issue.
- **Tunnel**: typically used between gateways to provide a secure connection (pipe) between physically separate networks, e.g., different sites of the same organization. Tunnel mode also supports secure host-to-gateway communication. An IP packet is encrypted in its entirety and encapsulated as a datagram with a new outer IP header. One popular application of tunnel mode is Virtual Private Networks (VPN).

IPv6 is a newer version of IP developed to overcome some limitations of IPv4. One of its main new features is extended 128-bit address space (as opposed to 32 bits in IPv4). Another departure from IPv4 is lack of in-network fragmentation. Before sending an IP datagram must first discover the smallest MTU on the path to the destination and fragment the datagram accordingly. To help with this, the Path MTU Discovery protocol was designed and implemented. IPv6 also takes into consideration security and privacy by implementing some features similar to IPsec – such as AH and ESP – as extension headers.

In the rest of this paper, we use the term “IP” to refer to both IPv4 and IPv6, unless otherwise specified.

### B. Domain Name System

The purpose of DNS is translation of domain names (e.g., those found in URL prefixes) into IP addresses. Domain names are organized in a hierarchical fashion: a top-level domain (e.g., “.com”) is followed by many sub-level domains (e.g., second-level domain “example.com”, and third-level domain “sub.example.com”). For each domain, DNS assigns an authoritative name server that stores information of, and responds to queries for, a specific contiguous portion of the domain name space, called DNS zone. This information is contained in Resource Records (RR-s) – basic DNS elements which are also carried in DNS replies. Moreover, authoritative name servers might delegate authority over sub-domains to other name servers, thus increasing DNS’s scalability.

A user interacts with DNS by issuing a query to a local resolver: a process running on the end-user’s device which forwards the query to the appropriate name server(s). The resolver sends a UDP (User Datagram Protocol) packet containing the query to the DNS server, which is usually located in the resolver’s local network. The server then checks if it can reply to the query from its cache. Otherwise, it fetches the response from other local or remote DNS servers.

DNS queries can be of two types: iterative or recursive. An iterative query allows a DNS server to return the best answer to the resolver, based on its local information, i.e., either a cached RR or an RR belonging to its zone. If the server does not have an exact match for the queried name, it returns a referral: a pointer to a DNS server authoritative for a lower level of the domain namespace. The resolver then queries the DNS server in the referral which can also reply with a referral. This process continues until the resolver receives requested information, or an error is generated. In the recursive query, DNS servers reply with either the requested RR or an error. If the DNS server does not have the requested information, it recursively queries other DNS servers.

Although DNS was originally designed as a static distributed database, it now allows dynamic records updates and zone transfers. Also, a recent proposal envisions DNS as a distributed database to store IP related information. For instance, proposes storing IPsec keys related information in DNS records and mapping them to IP addresses.

The original DNS did not include any security or privacy features. DNS Security Extensions (DNSSEC) was added to provide data integrity and origin authentication for DNS messages. In DNSSEC, RR-s are signed by their authoritative servers’ keys. The basic mechanism and the query-response protocol of DNS remain unaltered.

### III. NEBULA

Nebula is a FIA project focused on providing a secure and cloud-oriented networking infrastructure. Its architecture is composed of three tiers:

- **Network core (NCore)** is a collection of routers and interconnections that provide reliable connectivity between routers and data centers. NCore is based on high-performance core routers and rich interconnected topologies.
- **Nebula Virtual and Extensible Networking Techniques (NVENT)** represents the control plane of Nebula. NVENT helps in establishing trustworthy routes based on policy routing and service naming.
- **Nebula Data Plane (NDP)** is responsible for routing packets along the paths established by NVENT. To guarantee confidentiality, availability, and integrity, NDP ensures that packets for a specific communication can only be carried when all parties, i.e., end nodes and routers in between, have agreed to participate.

#### A. Nebula Network Layer

The original design of Nebula specifies different candidate network layer stacks for NDP, e.g., ICING, TorIP.
and Transit-as-a-Service (TaaS) [45]. From this list, ICING was picked as the most suitable candidate and was included in the Zodiac Nebula prototype implementation [3].

ICING provides a new primitive, called Path Verification Mechanism (PVM), which guarantees the following two properties:

- Path Consent – every entity in a path between two hosts consents the use of the whole path before the communication starts.
- Path Compliance – the possibility for each node in a path between two hosts to verify that a received packet: (1) follows the approved path; and (2) has been "correctly" forwarded by all the previous nodes in the path, i.e., according to a specific pre-established policy.

ICING can be deployed either at the network layer or as an overlay on top of IP. In the former case, service providers can deploy ICING nodes as ingress gateways to their networks. However, in the latter case, ICING nodes may become waypoints, interconnected using IP, providing waypoint-level path guarantees.

To start communication, a sender must first establish a complete path. Such a path can be provided by DNS with policy enforcement [43]. Figures 2(a) and 2(b) show how forwarding works in ICING and a high-level representation of how the ICING header evolves.

Once a path is selected, the sender requests a Proof of Consent (PoC) for each node j on the path (action 1) in Figure 2(a). PoCs are cryptographic tokens created by each node transit provider, which attest to the provider's consent to carry packets along the specified path. Each PoC certifies that the corresponding network provider consents to (1) the full path, and (2) a specific policy-based set of local actions (e.g., forwarding) to be performed on packets traversing the path.

PoCs are generated by a consent server, which is owned by the transit provider or acts on its behalf. Such servers share secret keys with each node (router) in their corresponding providers. Once all PoCs are received, the path is established and packet transmission can begin.

Each packet contains a header (shown in Figure 2(b)) including: (1) the path P consisting of all ICING nodes Nj forming it, and, (2) a list of verifiers Vj, one per node Nj in the path except the sender. This allows each verifier to prove that the packet passed through all previous nodes.

A sender builds a packet header as follows:

1) Proof of Provenance (PoP) token, one for each node on the path (action 2 in Figure 2(b)), is generated using a PoP key k j shared with the corresponding node j. In Figure 2(b) PoPs are denoted as PoP i,j, where i is the index of the node generating the PoP and j is the index of the node for which PoP is generated. Specifically, PoP 0,j is computed by node 0 using k j, path P, and message M itself.

2) Authenticator A j is computed for each node j using PoC j, P and M.

3) Verifiers Vj, one per node, are computed by XORing the corresponding A j and PoP i,j.

PoP tokens are used by each node on the path to prove that downstream nodes have handled the received packets based on the established policies. When an intermediate node N i receives a packet, it performs the following actions:

1) Computes the corresponding PoC i.
2) Computes PoP j,i using k j, for each downstream node N j.
3) Verifies that the received PoC i and PoP j,i match the two values computed in the previous two steps. If this verification fails, N i drops the packet.
4) Derives a shared PoP key k i for each upstream node N i, and computes PoP l,i as described above.
5) Modifies the verifiers to include the computed PoP, and forwards the packet upstream (actions 3 and 4 in Figures 2(a) and 2(b)).

The previous steps allow any node to guarantee that all packets are forwarded by all the consenting nodes while establishing the path.

B. Nebula Control Plane

The control plane in Nebula is provided by NVENT. NVENT uses declarative networking [46], [47], and allows administrators to provide high-level specifications of their routing policies. NVENT also involves special interfaces, called service interfaces, that enable service access and specify the required level of availability. For instance, an emergency service can request high availability, which can be provided by multi-path interdomain routing. A distributed resolution service is used for discovery of other NVENT services. This service is populated by service providers, e.g., NCore data centers [48].

Serval is an implementation of NVENT based on the concept of service-centric networking [49], [50], which decouples service instances (e.g., web or email services) from their physical locations (i.e., IP address and port). Serval introduces a new layer, the Service Access Layer (SAL), between the network layer and the transport layer. With Serval, each service is identified by a serviceID, a unique identifier that applications use to communicate with the service. In addition, each local traffic flow, representing a connection between two hosts, is identified by a unique flowID. The request is handled by SAL, which uses local control plane policies to map the serviceID to a service instance. SAL eventually creates a new flowID that identifies the established connection. This flowID is delivered to the destination host during connection setup, and used by both parties for connection identification. Finally, SAL routes the packet based on specific control plane rules contained in its SAL table. For instance, a host application that wants to connect to a specific service might direct the first request to a default Serval router (using its IP address). The SAL of the router then processes the request and take further decisions based on its SAL table (e.g., forward to another router or send directly to a known service instance). Moreover, Serval does not directly provide clients a way to learn serviceIDs: It simply suggests the use of directory services or search engines [42].

Figure 3 presents a view of how all Nebula components integrate to allow a user to negotiate a custom end-to-end path to a specific data center and send the desired packets. First, the user (either the mobile phone or the laptop in the figure) contacts NVENT to request a path to NCore. NVENT
determines a suitable path that complies with each transit network’s policies and contacts the corresponding consent servers to obtain the necessary PoCs. Once the path and all PoCs are delivered to the user, the latter generates appropriate packet headers and forwards them, using the NDP forwarders network, to the nearest NCore router. This router ensures that all header fields are valid (as described above) and verifies that the negotiated path has actually been traversed. Once verified, the core router forwards received packets to the correct data center using its NCore links.

Since names are opaque to the network, they can contain binary components.

To support content distribution, NDN defines two types of packets: interest and content (the latter is also called data packet). NDN communication adhered to the pull model, that is: every content is delivered to consumers only upon explicit request. Specifically, a consumer issues an interest packet carrying the name of the desired content. The network will then forward the interest towards the producer.

One important feature of NDN is in-network caching: any router can store a copy of the content it receives or forwards, and use it to satisfy subsequent interests. Therefore, an NDN interest might be satisfied by the actual content producer or any intermediate router. Along with in-network caching, NDN introduces another important feature called interest collapsing: only the first of multiple closely spaced (and timed) interests requesting the same content is forwarded by each router.

Each NDN entity (not only routers) maintains the following three components [4]:

- **Content Store (CS)** – cache used for content caching and retrieval. A router’s cache size is determined by local resource availability. Each router unilaterally determines what content to cache and for how long. From here on, we use the terms CS and cache interchangeably.
- **Forwarding Interest Base (FIB)** – table of name prefixes and corresponding outgoing interfaces. FIB is used to route interests based on longest-prefix matching of their names.
- **Pending Interest Table (PIT)** – table of outstanding (pending) interest names and a set of corresponding incoming interfaces, denoted as arrival-interfaces.

When an NDN entity receives an interest, it searches its PIT to determine whether another interest for the same content is pending. There are three possible outcomes:

1. If a PIT entry for the same name exists, and the arrival interface of the present interest is already in arrival-interfaces, the interest is discarded.
2. If a PIT entry for the same name exists, yet the arrival interface is new, the router appends the new incoming interface to arrival-interfaces, and the interest is not forwarded further.
3. Otherwise, the router looks up its cache for a matching content. If it succeeds, the cached content is returned and no new PIT entry is needed. Conversely, if no matching content is found, the router creates a new PIT entry and forwards the interest using its FIB.
Upon receipt of the interest, the producer (or an intermediate router) responds with a matching content, thus satisfying the interest. The content is then forwarded towards the consumer, traversing the reverse path of the preceding interest. Each router on the path flushes the corresponding PIT entry and forwards the content out on all interfaces specified by that entry. If a content is received by a router with no prior matching interest, the content is considered unsolicited and is discarded. Since no additional information is needed to deliver content, interests do not carry any form of source addresses.

The last component at the end of content name can carry an implicit digest (hash) component of the content that is re-computed at every hop. This effectively provides each content with a unique name. Names carrying such digest forms what is called as Self-Certifying Names (SCNs). If an interest is issued using SCN, the retrieved content is guaranteed, due to longest-prefix matching, to be the same content requested by the consumer. 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.

Apart from the name, content packets carry a Signature generated by the content producer and covering the entire content. For this reason, each producer is required to have at least one public key, represented as a bona fide named content object. Other notable fields in content packets are: the Payload containing the actual data of the content and the ContentType defining the type of the content, e.g. data or key. Other important fields in interest packets are: the KeyLocator which references to the public key required to verify the signature and the InterestLifetime which specifies the lifetime of an interest before it expires (and its corresponding PIT entry is flushed).

Similar to IP, fragmentation of NDN packets can not be avoided. The fact that names can grow arbitrary long might cause interests length to span beyond some link MTU values. In this case, fragmentation must occur. However, since FIB forwarding is based on the availability of the entire name, reassembling of fragmented interests at every hop is a must. Furthermore, interest collapsing can cause contents to be fragmented (or even re-fragmented) by routers. The question remains to whether to perform a hop-by-hop reassembly or cut-through processing of content fragments. Regardless of its claimed benefits, it is trivial to see that hop-by-hop reassembly incurs unnecessary overhead and end-to-end latency.

Not all interests result in content being returned. If an interest encounters either: (1) a router that can not forward it further or (2) a producer that has no matching content, no error is generated. PIT entries in intervening routers simply expire when no matching content is received. In such case, the consumer can choose to re-issue the same interest after a timeout.

B. NDNS Distributed Database

Since content can be addressed using human-readable names, NDN in principle does not require a resolution service that translate user-friendly names into network addresses. However, as discussed in [53], a distributed database similar to DNS, if existed, provides several benefits to the NDN architecture:

- Cryptographic credential management: Since each data packet is required to be signed, a distributed database is optimal to store and serve security information (e.g., keys and certificates) for namespaces.
- Namespace regulation in the global routing: Similar to the ROVER project [54], a DNS-like service can store information that certifies the authorization of ASes to announce a particular prefix in the global routing.
- Scaling NDN routing: The fact that NDN names can be arbitrary long renders the namespace infinitely large. This exceeds the number of possible routable IP prefixes. Therefore, a DNS-like service can be used to implement a Map-n-encap solution to increase scalability in NDN routing [55].

Two distributed database systems that resemble the DNS design, KRS and NDNS, are proposed in [53], [56], respectively. These two proposals adopt a similar design and provide the same features. In the rest of this paper we use NDNS to refer to such a distributed system.

Similar to domain names in DNS, NDNS organizes namespaces in a hierarchical set of zones and assigns replicated authoritative servers for each of them. NDNS queries are expressed via interest, in which, names carry all query’s necessary information. NDNS responses are carried in content objects where their payloads contain the information requested by the corresponding query.

NDNS reflects many of the DNS protocol machineries: a resolver issues an iterative or recursive query to a local NDNS server. In case of iterative query, the server can reply with the answer (if known), a referral, or a negative response. In case of recursive query, if the NDNS server does not know the answer, it recursively query another NDNS server until it receives an answer (i.e., the requested data or a negative response). Moreover, secure dynamic updates are provided as in DNS [57].

V. MobilityFirst

MobilityFirst architecture aims to overcome the inefficiencies and limitations of today’s Internet due to mobility. It focuses on scenarios where wireless connections are ubiquitous and pervasive. To this end, MobilityFirst has been designed around the concepts of mobility and trustworthiness. All endpoints must be able to seamlessly switch network connection, and the network must be resilient to compromised endpoints and routers.

MobilityFirst treats principals – devices, content, interfaces, services, human end-users, or a collection of identifiers – as primary addressable network entities. To promote mobility, the (constant) identity of a principal and its (dynamic) network location are strictly separated. This requires a distributed Global Name Service (GNS) to bind principal identities to network addresses. Furthermore, identity and network address separation (1) facilitates service implementation and deployment, and (2) supports designing routing protocols that overcome link fluctuation and disconnections [58].
We now briefly describe MobilityFirst’s network layer and its Global Name Service.

A. Network Layer

Two types of identifiers are used to differentiate between principal identities and their physical locations.

- **Global Unique Identifier (GUID):** a flat self-certifying identifier that uniquely identifies a principal. GUIDs can be generated using multiple methods depending on the provided service type. For instance, they can be derived from the public key of a host or a service principal or the hash of a content principal. For the sake of usability, a human readable name can be assigned to a principal and later resolved (by GNS) to the corresponding GUID.

- **Network Address (NA):** a flat address that identifies a network to which a particular principal (GUID) is connected. MobilityFirst networks are equivalent to ASes on today’s Internet. NAs can be used to identify fine-grained networks such as subnets or organizations. In cases where principals are connected to multiple networks (e.g., using 3G and WiFi simultaneously), multiple NAs can correspond to the same principal.

As a consequence of this addressing scheme, MobilityFirst defines a new packet type called Packet Data Unit (PDU). PDUs contain source and destination GUIDs, lists of source and destination NAs, payload, and other control fields.

In order to communicate with a specific GUID, endpoints need to query GNS to obtain the corresponding NA. The retrieved tuple (GUID, NA) is then carried in the PDU header as a routable destination identifier. PDUs are first delivered to their corresponding destination NAs (using inter-domain routing), and then to the destination GUIDs (using intra-domain routing). In case of delivery failure, the packet is stored inside the network (in routers) and GNS is periodically queried for a new or updated GUID-NA mapping.

Multihoming, anycast, and multicast are supported by multicast GUIDs (MIDs). MID has the same format as a regular GUID, except its resolution results in a set of NAs (instead of, at most, one). Technically, GNS associates one MID with several GUIDs (the ones belonging to the multicast group). Resolving all of them results in one or more elements of the output NAs set.

MobilityFirst can also support content distribution networks. In this case, GUIDs are composed of two parts:

- **Content GUID (CID):** uniquely identifies the content and is generated by computing the hash of the corresponding content.

- **Publisher GUID (PID):** points to the network entity providing the content. Such an entity can be the actual content provider, or a third-party content repository.

A router may be equipped with a cache. This opportunistic caching feature facilitates content distribution at the network layer by reducing end-to-end latency and bandwidth consumption. Moreover, MobilityFirst exploits in-network caching to implement a per-segment (i.e., a continuous set of links with caching routers at each end) reliable chunk (few hundred of megabytes) transfer. Each chunk is fragmented and transmitted according to the segment MTU. Then, the caching router at the other end assembles the entire chunk and stores it. In case of transferring failure, caching routers can re-transmit a chunk via the same, or even a different, path.

B. Global Name Service

GNS is an essential part of the MobilityFirst architecture. Its main task is to map endpoint identifiers (GUIDs or human readable names) to a set of attributes including the endpoint network address. GNS relies on the following two services:

- **Name Certification Service (NCS):** is equivalent to a Certificate Authority (CA). Its purpose is to (1) assign GUIDs to human-readable names and (2) attest this mapping by generating certificates. MobilityFirst allows multiple NCSs without a global root of trust. Moreover, if GUID space is large enough, the need for coordination between different NCSs is eliminated.

- **Global Name Resolution Service (GNRS):** a distributed naming service similar to Domain Name System (DNS) that stores the mapping between GUIDs and NAs. Two GNRS implementations are evaluated: (1) a distributed hash table maintained among all ASes of the Internet (DMap), and (2) a number of replica-controllers that migrate data (GUID-NA mappings) between a variable number of active replicas (Auspice).

Regardless of its implementation, GNRS clients interact with the service by issuing the following requests to the GNRS resolver:

- **insert:** register a new GUID-NA mapping when a principal joins the network.

- **update:** keep the GUID-NA mapping up-to-date when the corresponding principal migrates to a new network location.

- **query:** retrieve the list of NAs associated with a specific GUID.

In [60], a secure version of the above three GNRS request types is proposed. The secure insert and update requests adopt a two-step approach to check validity of a GUID-NA mapping. Four network entities are involved in this process: (1) the user issuing the new GUID-NA mapping, (2) the local router to which the user is connected, (3) the border gateway router that connects the user’s AS to the rest of the Internet, and (4) the DHCP server which assigns the user’s address.

The user generates and signs the request containing the GUID-NA mapping. Local and border routers are in charge of verifying validity of the announced mapping. This is achieved by verifying that the announced NA is the network connected to the user (and the local router), and querying the DHCP server to ensure that the returned NA corresponds to the announced GUID. If the NA matches the one contained in the update or the insert request, the mapping is accepted and added or updated in the GNRS table.

In the secure query request, the protocol involves three entities: the user, the border gateway, and GNRS. The user

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1. GNRS is the actual GNS service that is responsible for maintaining GUID-NA mappings.

2. A router may be equipped with a cache. This opportunistic caching feature facilitates content distribution at the network layer by reducing end-to-end latency and bandwidth consumption. Moreover, MobilityFirst exploits in-network caching to implement a per-segment (i.e., a continuous set of links with caching routers at each end) reliable chunk (few hundred of megabytes) transfer. Each chunk is fragmented and transmitted according to the segment MTU. Then, the caching router at the other end assembles the entire chunk and stores it. In case of transferring failure, caching routers can re-transmit a chunk via the same, or even a different, path.
issues an authenticated request and the border router checks its validity. The router then forwards the request to the appropriate GNRS replica. On receipt, the GNRS satisfies the request with a signed GUID-NA mapping response.

There are several differences between GNRS and DNS [9]. First, GNRS does not restrict the structure of the names, while DNS only supports hierarchical names. Second, scalability of GNRS does not rely on TTL-based caching, which has been proven to be ineffective in the presence of high mobility. Third, GNRS does not statically give the authority to a replicated server for a specific set of names. Active and on-demand replication reduce reliance on passive caching and ensure that mapping replicas are always accessible close to clients.

VI. eXpressive Internet Architecture

eXpressive Internet Architecture (XIA) is another research effort aiming to design a new architecture. XIA is based on three types of principals. Host-centric networking can support end-to-end communication, such as video conferencing and file sharing. Service-centric networking allows users to access various network services such as printing and data storage services. Meanwhile, content-centric networking can support Web browsing and content distribution. However, XIA’s design is extensible in that it can adaptively provide network evolution and support any new principal type that might emerge in the future.

A core architectural property of XIA is intrinsic security of all principals. Any entity should be able to authenticate the principal it is communicating with, without trusted third parties. This can be achieved by binding one or more security properties with principal names. For instance, using the hash of a service (or a host) public key as its name allows entities to verify that they are communicating with the desired principal. Similarly, binding content with its name can be achieved using the hash of the content as its name, allowing users to verify the integrity of a requested content.

XIA defines three main design requirements:

1) All network entities must be capable of clearly expressing their intent. This is achieved by designing the network to be principal-centric and allowing in-network optimization. Routers can perform principal-specific operations when receiving, processing, and forwarding packets.

2) The network must be able to adapt to new types of principals. This is essential to support network evolution.

3) Principal identifiers must be intrinsically secure. This depends on the principal type, e.g., authenticating hosts in host-centric networking is different than verifying content integrity in content-centric networking.

Principal identifiers are denoted as XID, where X defines the type of principle. For instance, HID identifies a host, SID a service, NID a network, and CID a content.

A. eXpressive Internet Protocol

In order to comply with the aforementioned requirements, eXpressive Internet Protocol (XIP) is designed. XIP defines packet format, addressing schemes, and behavior of all nodes while processing incoming and outgoing packets from/to various principal types. One of the main features of the XIP addressing scheme is flexibility of defining multiple (fallback) paths to destinations. This prevents downtime and service interruption, especially while gradually deploying new principal types. An XIP address is a directed acyclic graph (DAG) with several properties:

- Each address is a single connected component.
- Each DAG starts with an untyped entry node and ends with one or multiple “sink” nodes. Thus, each node in the address graph has a unique XID except for the entry node.
- Edges define next hops in the path.
- Multiple outgoing edges of a single node are processed in the order they are listed.
- Out-degree of each node is upper bounded to restrict performance overhead.

Using DAGs as a basis for XIP addresses allows applications to build several “styles” of addresses, such as:

- **Shortcut routing** – this style, shown in Figure 4(a) is best suitable for requesting content principal. Each node has a direct edge to the destination principal CID1, which enables in-network caching. If a node does not have the content cached, the fallback path is processed and the packet is forwarded to the next hop.

- **Binding** – some services require that communication is bound to a specific source or destination. For instance, a service hosted in multiple geographical locations. Users can establish a session with the closest host providing this service. Then, all further communications must be directed to this particular host. Figure 4(b) shows an example of this addressing style. The first packet is destined to SID1, i.e. the closest host, while the second packet is destined to SID1 provided by a specific host HID1.

- **Infrastructure evolution** – as mentioned above, XIA supports gradual network evolution for emerging principal types using fallback paths. Figure 4(c) shows an example of this style. Assume that NID1 is gradually deploying service SID1. All NID1 routers that are not yet updated to recognize and process SID1 use the fallback path through HID1 and HID2.

- **Source routing** – Figure 4(d) gives an example of this addressing style, in which the source routes the packet to the destination through a third party domain and service, NIDn and SIDn, respectively.

- **Multiple paths** – this supports recovery from link failures. An example of this style is shown in Figure 4(e).

Figure 5 shows a high level overview of an XIA router. Its modular design allows efficient multi-principal processing and supports network evolution. Each router contains two main XID-specific processing modules:

- **Source XID-specific processing**: necessary for certain XID types. For instance, in case of a reply to a CID request, the “CID processing” unit can implement in-network content caching.

- **Next Destination XID-specific processing**: invoked by
the Next Destination XID-specific Classifier which determines the appropriate forwarding action. Similar to source processing, this module consists of several units that carry on XID-specific operations right before forwarding the packet.

If all outgoing DAG edges of a node lead to recognizable XIDs, the packet is dropped and an unreachable destination error is generated. It is the responsibility of user applications to provide appropriate fallback paths to avoid forwarding failures at any router. Usually fallback paths are built using well-supported principals, e.g. HID and NID.

**B. Principals**

As mentioned above, principals in XIA support emerging communication paradigm on the current Internet. When introducing a new principal, the following issues arise:

- What does it mean to communicate with a principal of this type?
- How is the principal’s unique XID generated and how does it map to intrinsic security properties?
- What are the source and next destination XID-specific processing actions that routers should perform and how can such actions be implemented?

We now describe several principal types and discuss their addressing schemes, in-router processing behaviors, and security properties.

1) **Network and Host**: Network and host principal identifiers are denoted as NID and HID, respectively. They are generated by using the public key hash of the network or the host. Unlike hosts on current Internet, each XIA host has a unique HID regardless of the interface it is communicating through. This feature helps support host mobility. In order to support fallback paths, all XIA routers should implement NID and HID processing modules.

As mentioned above, the fact that the network and host addresses are derived from their corresponding public keys allows users to verify the identity of entities with whom they are communicating. Furthermore, this security requirement helps defend against address spoofing, Denial of Service (DoS), and cache poisoning attacks.

2) **Service**: Services in XIA represent applications in today’s Internet. Users communicating with a service SID can use a destination address of the form NID:HID:SID. In today’s terminology, this is analogous to sending a packet to a specific host in a specific network and indicating the associated protocol and port number.

Since different services might require different specialized processing, implementing in-router source and next destination processing modules is a challenge. Therefore, routers are only required to perform default processing, routing, and forwarding of SID packets. All other specialized processing should be handled by end-nodes.

SIDs are generated by computing the hash of the service public key. This inherits security properties similar to NIDs and HID.

3) **Content principals**: This principal type signifies user’s intent to retrieve content. Packets carrying content identifiers

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**Fig. 4. XIP Addressing Styles**

**Fig. 5. XIA Router Diagram**
(CID) as destination addresses will be routed all the way to the node hosting the content. Routers can use a cached version of the content as a reply to such packets. As mentioned above, caching is implemented by routers' source XID-specific processing module.

CIDs are generated based on the cryptographic hash of the content they address. This binds the content to its name, forming a self-certifying name.

VII. NETWORK-LAYER SECURITY AND PRIVACY

According to NSF, one of the guiding principles for a new Internet architecture is to provide security and privacy by design. For this reason, FIA involved projects do not only focus on improving the network performance, but also on increasing network security and privacy guarantees.

In this section, we provide a comparison between the security and privacy features offered at the network layer of each architecture introduced above, and compare them with IP and IPSec. We consider the following security and privacy features that we believe essential to obtain a secure and privacy-preserving communication [64].

- **Trust**: A feeling of certainty (sometimes based on inconclusive evidence) that an entity will behave exactly as expected.
- **Data origin authentication**: The corroboration that the source of the received data is as claimed.
- **Peer entity authentication**: The corroboration that a peer entity in an association is the one claimed.
- **Data integrity**: The property that data has not been changed, in an unauthorized or accidental manner.
- **Authorization and access control**: An approval that is granted to an entity to access some resources and the protection of such resources against unauthorized access.
- **Accountability**: The property that ensures that entity actions can be traced to said entity, which can then be held responsible.
- **Data confidentiality**: The property that information is not made available or disclosed to unauthorized entities.
- **Traffic flow confidentiality**: A confidentiality service to protect against traffic analysis.
- **Anonymous communication**: The guarantees that entity identities being unknown or concealed.
- **Availability**: The property of being accessible and usable upon demand by an authorized entity.

A. Trust

IPsec defines trust as a one-way relationship between two or more entities (hosts or networks). This relationship is represented using a Security Association (SA). SAs contain a set of information that can be considered as a “contract” between the involved entities. This describes security services and contains security information needed by hosts to protect the communication.

Entities involved in secure communication in IPsec establish SAs via the ISAKMP [65] protocol and exchange necessary cryptographic material using the Internet Key Exchange (IKE) protocol [66]. Host authentication in ISAKMP and IKE can be achieved via either digital signatures, or pre-shared keys. Digital signatures require the use of certificates to bind entity identities to their public keys. This implies the existence of a CA to create, sign, and properly distribute certificates.

Nebula’s ICING-based network layer defines trust in a way that is orthogonal to IPsec. Trust is defined between a host and all nodes forwarding its packets. As described in Section III a host agrees on a “contract” with the network providers carrying the data (i.e., the path negotiated using NVENT) to specify the operation executed at each hop. Such contracts are cryptographically enforced. ICING assumes mutual trust between forwarding nodes and their consent servers, i.e., servers responsible for creating PoC tokens. Therefore, this notion of trust does not require any PKI [43]. However, ICING does not provide an end-to-end definition of trust, which can be added by adopting an IPsec-like approach.

Unlike IP, the notion of trust in NDN is not directly associated with hosts and networks, but rather with content. Trust in content can be expressed at different levels of granularity, from a single content to an entire namespace. Recall that a content object is signed by its producer which allows anyone to verify its origin and authenticity. Origin verification refers to content producer rather than whoever stores a copy of that content. In order to authenticate a content and its origin, its signature must be verified. To do so, the verification (public) key must be retrieved and trusted. However, trust management is not specified at the network layer and is left to applications. NDN network-layer trust management is discussed in [67].

MobilityFirst places trust in principal. Depending on their type, trust may be established with (1) hosts, similar to IPsec, (2) content, similar to NDN, or (3) centralized or distributed services. Trust semantics in XIA also vary depending on principal types. However, the intrinsic security feature of these principals (described in Section VI) increases trustworthiness of end-to-end communication and content retrieval. For instance, ensuring that a content hash matches its identifier allows receivers (and caching routers) to trust that content.

As shown in Section VII an XIA address consists of a DAG containing a (partial) path to the destination. To provide trusted path selection for host-to-host communication, SCION is integrated with XIA [68]. SCION [69] is an architecture that provides control and isolation for secure and highly available end-to-end communication. The network is divided into multiple trust domains consisting of several Autonomous Systems (ASes) that trust each other. Each domain has a trusted root AS responsible for relaying packets to and from other domains. Roots initiate path establishment to all hosts in their domains based on local policies and available bandwidth. This process results in constructing a path between each host and its domain root. Whenever two XIA hosts, in different domains, want to communicate, the two half paths (from each host to its domain root) are combined to establish a complete end-to-end path. Such path is trusted since it is created by the trusted roots of each domain.

*Keys in NDN are distributed in content objects with type KEY. Such objects (keys) are signed by their issuer, e.g., CA.*
B. Data origin authentication

IP (IPv4 in particular) does not provide any form of authentication. A separate add-on method, IPsec, provides entity authentication via AH and ESP protocols. In transport mode, two hosts securely negotiate a shared secret key. This key is later used to generate a Message Authentication Code (MAC) for each packet. Successful MAC verification ensures authenticity of received packets and their origin. In case of gateway-to-gateway communication, gateways can only verify that the received data originated by any (not a specific) host connected to the network at the other end of the tunnel. In host-to-gateway communication, the gateway can actually verify that the data originated by the involved host, while the latter can only verify that received data is originated by the network located behind the gateway. This partial authentication opens the door for insider attacks.

Nebula’s ICING-based network layer does not directly provide data origin authentication. Instead, it is delegated to applications. ICING allows a sender to authenticate entities issuing cryptographic tokens, i.e., PoCs. However, the design does not specify how PoCs are retrieved or authenticated.

NDN provides origin and data authentication via content signatures. Before consuming content, consumers are required to verify its signature. However, this operation is optional for routers because signature verification is an expensive operation at line speed and comprehensive trust management is not viable at the network layer. Even if we assume that routers know all possible application trust models, establishing trust in content is complicated and expensive. For instance, traversing a PKI hierarchy requires routers to fetch and verify public key certificates until a trusted anchor is reached.

On the other hand, NDN interests can optionally be authenticated using digital signature. In a signed interest, the last component of the name carries a signature computed by the consumer. Although this reveals consumer identities, signing signatures (or any other form of identities) are usually required in some scenarios such as access control.

MobilityFirst and XIA do not provide any data origin and entity authentication at the network layer. However, their usage of self-certifying identities as principal identifiers facilitates entity authentication. Recall that for host, network, and service principals, identifiers are generated by computing the hash of the public key associated with these principals. Therefore, entity authentication can be achieved by ensuring that such principal identifiers match their keys. Also, peer authentication for content principals can be achieved similar to NDN. Note that neither MobilityFirst nor XIA provides a secure mechanism for securely retrieving content identifiers.

D. Data integrity

Although IPv4 header contains the Header Checksum field that provides transmission error detection (a form of integrity check), it does not prevent packet manipulation. In fact, both versions of IP, introduced in Section II-A, completely delegate integrity to IPsec AH and ESP protocols. Specifically, the HMAC values in these protocol headers are used to achieve integrity. Depending on the IPsec mode used, host-to-host, gateway-to-gateway, or host-to-gateway integrity guarantees can be provided by both AH and ESP protocols. However, AH provides integrity for the entire packet (except for mutable fields), while ESP guarantees packet headers integrity only.

Each packet in Nebula carries a sequence of cryptographic verifiers, $V_j$, one for each hop on the path (see Section II-A for details). The packet hash is used as part of $V_j$’s calculation. Therefore, ICING guarantees that neither the packet nor the path can be modified. Also, ICING is recommended only at domain gateways. Thus, integrity can only be guaranteed by border routers. Within domains, such guarantees are deferred to either the network-layer protocol or the application.

The way NDN provides integrity is through content signature. By verifying this signature, consumers and routers can always detect malicious manipulation. However, when content is requested using SCNs, data integrity is achieved.
by comparing the content hash to the last name component of its name. Furthermore, only signed interests can provide interest integrity.

In both MobilityFirst and XIA, integrity is only available for content principal types. This is again due to the fact that such a principal identifier is generated based on the content hash itself. Whenever a content is received, its hash is compared with its identifier to ensure content integrity. For other principal types, MobilityFirst and XIA defer integrity guarantees to the application.

E. Authorization and access control

Access control in IP is achieved by restricting access based on source and destination addresses. This is implemented using Access Control Lists (ACLs) [72], which contain a set of rules that grant or deny access to network resources. When implemented in routers, ACLs specify whether a received packet will be forwarded further to the next hop, or simply getting dropped. Whereas host ACLs are used to decide whether to forward packets up the stack towards the application. Since IP does not natively provide packet integrity, address spoofing can be used to circumvent ACL rules. Employing IPsec, however, prevents such actions.

In Nebula, paths must be established before communication begins, i.e., clients must obtain required PoC tokens. Therefore, access control can be implemented by the consent server granting or denying PoC requests. Traffic sent without valid PoC tokens can be easily detected and dropped.

Unlike IP, enforcing access control in NDN should be done based on content and not network entities. Although not implemented in practice, ACLs can still be used to implement access control. In this case, rules are applied on interest messages and content objects based on the names they carry. Longest-prefix can also be employed to grant or restrict access to entire namespaces. Due to the fact that NDN interests do not carry source addresses, access control on the consumer granularity can only be achieved in cases where interests are signed or carry some form of consumer identity [73].

One way of providing access control in NDN is by using encryption. Producers can encrypt their content and disseminate decryption keys to authorized consumers only. Such keys can be encapsulated in content objects and should not be cached. One drawback of this approach is that it requires consumers to issue at least two interests for each content (one to request the content itself and one to request the corresponding key).

Since MobilityFirst and XIA can support different principal types, they facilitate the combination of both NDN- and IP-based access control schemes. For content principals, access control is done at the content granularity, similar to NDN, e.g., content is encrypted using keys disseminated to only authorized users. For all other principal types, ACLs can restrict access to hosts and other network services.

F. Accountability

One of the main problems in IP is accountability. In fact, IP is subject to source address spoofing that lead to the inability of tracing back the entity responsible for a particular action. A simple countermeasure against IP spoofing requires ASes to implement egress filtering and ensure that all outgoing traffic carries source addresses owned by these ASes. IPsec guarantees peer entity authentication when establishing SAs between hosts. Thus, accountability can be achieved.

Nebula provides accountability through path establishment. All routers on a path consent to use the whole path before the communication begins. Moreover, the fact that these routers pre-agree on performing a specific set of actions on each packet passing through allows the detection of any malicious activities.

NDN provides full accountability of producers. Since every content is signed by its producer, tracing the producer responsible for generating content is a trivial task. However, accountability can not be provided if content is served from router caches. Consumers accountability, on the other hand, can only be achieved when they issue signed interests, or include their identities in the interests themselves. Otherwise, accountability can not be provided.

Both MobilityFirst and XIA do not provide accountability at the network layer. However, signing requests and responses can provide this feature in a similar fashion to NDN, especially for content principals. Also, IPsec-similar techniques can be employed to provide accountability for other principal types.

G. Data confidentiality

The natural way to achieve data confidentiality at the network layer is by using encryption.

IP does not provide data confidentiality. This is done by using IPsec. The level of confidentiality depends on the mode of operation. In transport mode, ESP only encrypts the IP packet payload and data confidentiality is host-to-host. Tunnel mode extends confidentiality to the entire encapsulated IP packet, including both payload and header. However, data confidentiality can only be achieved in host-to-gateway or gateway-to-gateway scenarios. Also, ESP confidentiality is not generally effective against active adversaries. It has been demonstrated that achieving confidentiality without a strong integrity mechanism, or even applying integrity before encryption, can only protect against passive adversaries [74]–[76]. Thus, even though IPsec provides confidentiality, poor usage practices can negate its benefits.

Nebula’s ICING-based network layer does not natively provide data confidentiality. Instead, it can be achieved by combining ICING with end-to-end encryption of the packet payload.

Data confidentiality in NDN can be attained by encrypting content payload. This is not supported by the architecture and is left to the application. However, even if content is encrypted, the fact that it carries a human-readable name might leak information about its data.

MobilityFirst and XIA provides content principal confidentiality using methods similar to the those used in NDN. Fortunately, and due to the fact that such principal identifiers are generated using the hash of the content itself, inspecting them does not leak information about the encrypted content. Moreover, confidentiality of data communicated between host,
network and service principals can be achieved using similar techniques to IPsec.

H. Traffic flow confidentiality

It is well known that encryption does not protect against statistical traffic analysis – attacks that monitor traffic in order to extract properties, such as volume and timing [72].

IPsec provides some traffic flow confidentiality by padding packet payloads to hide their size patterns. However, according to IPsec specifications, this is not mandatory and, therefore, may not be supported in all IPsec implementations [8].

NDN, MobilityFirst, Nebula and XIA are all susceptible to traffic analysis attacks. Fortunately, padding can be used to provide traffic and flow confidentiality.

Another architecture-agnostic alternative is to add artificial delays to communications to better hinder time-based attacks. This, however, comes at the expense of increasing end-to-end latency and reducing overall network performance, especially for time-sensitive traffic.

I. Anonymous Communication

IP (with or without IPsec) does not support anonymous communication. This is mainly because source and destination addresses are in the clear in packet headers. However, partial anonymity can be achieved using the tunnel mode of IPsec along with ESP. This is because tunnel mode allows the ESP protocol to encrypt the original IP packet along with the source and destination addresses, and it encapsulates that packet into a new one with a new header reflecting gateway addresses. This combination hides end-host identities among the set of other hosts connected to respective end-networks. However, this is only effective if the adversary is eavesdropping on the link between the two gateways and is not located inside one of the end-networks. Furthermore, in case of host-to-gateway tunnel mode, only anonymity of hosts located behind the gateway is preserved.

Crowds [78] is one of the first proposals to achieve user anonymity. In it, a message is randomly forwarded between group members before it reaches its destination. Therefore, none of the group members nor the end recipient learn the actual source of the message. The Onion Router (TOR) [79] is another method that provides anonymous communication through a “circuit.” Circuits are multi-hop encrypted communication channels established using at least three TOR nodes. Theoretically, TOR guarantees anonymity with respect to an adversary controlling, at most, two TOR nodes. However, flawed TOR implementations can reduce its provided anonymity level [80].

Hosts anonymity is not provided by ICING-based Nebula. By inspecting packet headers, eavesdroppers can easily determine a packet’s source, as well as the path it traversed. However, host anonymity can be achieved by replacing ICING with TorIP [44], thus resulting in a level of anonymity similar to that provided by TOR in today’s Internet.

Unlike IP, NDN has some features that facilitate anonymous communication. A PIT allows interest messages and content objects to only carry the requested content name without any consumer-related information. However, Compagno et al. show in [81] that adversaries with enough knowledge of the network can determine consumer’s location. DiBenedetto et al. proposed ANDâNA [82], a tool that provides a level of anonymity similar to TOR, while requiring only two intermediate nodes, instead of three.

MobilityFirst and XIA suffer from the same privacy and anonymity problems as IP. Packets contain both source and destination GUIDs (or principal identifiers), thus revealing the hosts involved. To make the matter worse, XIA packets path can be revealed by inspecting their destination DAG addresses. This is because such addresses might include (part of) the path to the destination, as described in Section VII. Due to the communication model similarity of these two architectures to IP, approaches developed to preserve users anonymity in IP networks can be adopted. For instance, TOR can be used to protect MobilityFirst and XIA host principals’ anonymity. Preserving content principals’ anonymity can be achieved using a protocol similar to ANDâNA in NDN [82].

J. Availability

Denial-of-Service (DoS) and Distributed DoS (DDoS) present a well known threat against availability. In the following, we discuss DoS and DDoS attacks that apply to the network layer of the current as well as (some of) the future Internet architectures discussed above. We also shed the light on new (and possibly more serious) type of attacks that the new architectures allow. We exclude discussing the lack of availability due to network misconfigurations, disasters, hardware and software faults, or any other causes that are not a direct consequence of an attack.

Bandwidth depletion attacks. The current Internet architecture is susceptible to bandwidth depletion attacks [83]. Their goal is to exhaust bandwidth of a specific link. These attacks can be mounted in two ways: (1) distributed – with packets sent at low rate by each attacking node, or (2) centralized – a single powerful adversary flooding the target link at high rate. Due to today’s high bandwidth and redundancy, centralized bandwidth depletion attacks are harder to mount.

Several mitigation and prevention techniques have been proposed and implemented in the current Internet. Some examples are: (1) tracing back traffic to the source of the attack [84]–[86], (2) distinguishing between legitimate and malicious traffic [87], [88], (3) using puzzles to increase the cost for adversaries trying to consume bandwidth [89], [90], and (4) using rate-limiting mechanisms for traffic that causes congestion [91]–[93]. However, none can effectively defeat this attack.

Bandwidth depletion in the data plane is harder to mount in Nebula, because senders (adversaries) must obtain consent of all nodes on a path before sending packets. Thus, unauthorized packets will be dropped by adversary-facing routers. Unfortunately, this only shifts the attack from the network layer to the consent servers and causes negative effects on the network. The reason is because a single consent server might be responsible for a large number of routers in its
domain. Thus, lowering its ability of issuing PoCs can disable all routers in that domain.

NDN design is more resilient to bandwidth depletion attacks as compare to its IP counterpart. Recall that NDN communication adheres to the pull model, i.e., a content is forwarded only in response to a corresponding previous interest. This model prevents adversaries from flooding the network with unsolicited content. In addition, flooding the network with a large number of interests to cause bandwidth depletion is not very effective due to the small size of interest packets.

Since MobilityFirst and XIA use a communication model similar to IP, they both are susceptible to bandwidth depletion attacks. Similar countermeasures applied in IP networks can be adopted. However, they can only reduce the effect of these attacks.

Nugraha et al. [94] suggested integrating STRIDE with XIA to protect against DoS attacks. STRIDE [95] is an architecture resilient to bandwidth depletion (D)DoS attacks. It modifies SCION path establishment to perform a tree-based bandwidth allocation. Whenever a trusted domain root initiates the path establishment process, bandwidth is allocated as the path is branching out as a tree from that root. This guarantees the required bandwidth for benign flows. STRIDE also supports long-term static paths to provide high available connectivity.

Routers resource exhaustion. Exhausting storage resources of routers is another target for adversaries. NAT-enabled router might assemble fragments in some scenarios. Reassembly buffers in these routers can be exploited as follows. Each fragment includes a 16-bit field to indicate the size of the original packet. Adversaries can send a single fragment with a large original packet size and never send the rest of the fragments. This forces assembling routers to allocate a buffer and wait for the rest of the packet to arrive. To make the matter worse, adversaries can set the original packet size to its maximum value, 64KB, thus allocating maximum buffers.

Computation resources of routers is another victim of exhaustion. Since ICING’s design requires the extensive use of cryptographic operations, adversaries can send a large number of packets to routers forcing them to perform all verification operations described in Section III. Such attacks have very low cost on adversaries since the latter can flood victim routers with packets carrying invalid (e.g., randomly generated) PoC and PoP values.

As mentioned above, PIT is one of the main router components that enables content delivering without requiring any form of consumer source addresses. PIT is also used for interest collapsing in order to reduce bandwidth due to a burst of closely-spaced interests for the same content. However, the fact that PIT is a limited and valuable resource makes it susceptible to malicious exhaustion. Adversaries can send a large number of interests attempting to fill the PIT. To avoid collapsing, such interests can refer to nonsensical content. Once the PIT is full, a router can either: (1) drop incoming interests, or (2) remove old PIT entries to make space for new ones. Both options, however, can adversely impact past or future interests. This type of attack is called Interest Flooding (IF) [96], [97].

Unfortunately, there is no comprehensive remedy for IF attacks. Although several countermeasures have been proposed, they are ineffective against smart adversaries and only manage to lower the volume of IF attacks [98]-[100]. One possible remedy for IF attacks is to eliminate the PIT – its root cause. For this reason, [101] suggests a modified Content-Centric Networking (CCN) architecture without router PITs.

Cache-related attacks. Regardless of the aforementioned benefits of in-network caching, it opens the door for new types of DoS attacks that do not exist in today’s Internet network layer: content poisoning and cache pollution. In the following we describe the resiliency of NDN, MobilityFirst, and XIA against these attacks. We exclude Nebula since its design does not provide in-network caching.

a) Content poisoning: Content poisoning attacks occur when adversaries inject fake content into router caches. A fake content is not generated by a benign producer and, consequently, does not satisfy user requests. If such content is cached in routers, it is used to reply to future benign user requests.

The fact that NDN adheres to the pull model makes it harder, but still feasible, for adversaries to inject fake content into router caches. There are two methods to achieve this:

- Reactive: the adversary Adv is a node eavesdropping or controlling a link, e.g., an upstream malicious router. Adv responds to interests on that links with a fake content that is cached in all downstream routers.
- Proactive: this method involves Adv that, anticipating demand for certain content, issues one or more bogus interests (perhaps from strategically placed zombie consumers), before genuine interests are issued. Adv then replies with fake content (from a set of compromised routers or compromised producers) thus pre-poisoning the caches of all routers forwarding the bogus interests.

What facilitates this attack is the fact that content signature verification is not mandatory by routers. This is because not only signature verification is an expensive operation at line speed, variant trust models adopted by different applications renders trusting public (verifying) keys a challenge. Even if we assume that routers can know about all possible trust models, some might incur heavy and expensive network operations. For instance, PKI hierarchy requires routers to iteratively fetch and verify public keys until a trusted anchor is reached. Such an impractical approach significantly reduces the network performance.

Ghali et al. identifies in [67], the root causes and proposes a solution for content poisoning. The main idea is to have consumers and producers collaborate in providing routers with enough trust contextual information to perform a single signature verification. This process is formalized by a rule called the Interest Key Binding (IKB) rule.

An alternative solution is the use of SCNs. By definition, a SCN contains a value that (uniquely) identifies the principal it is referring to. In case of content principal in MobilityFirst and XIA, and content objects in NDN, SCNs contain the hash

5We assume that in the future, public key operations will be available at the hardware level.
of the data itself. When users request content using SCNs, the network guarantees that the requested content will be correctly delivered. As a result, MobilityFirst and XIA eliminate the effects of content poisoning attacks by design. It is worth mentioning that using SCNs does not prevent adversaries from injecting fake content in router caches. Instead, it guarantees that benign users will not receive such fake content.

b) Cache pollution: Pollution is another type of (D)DoS attacks against router caches. In such attacks, adversaries attempt to manipulate reference locality of caches, causing incorrect decisions made by cache eviction strategies. This causes routers to possibly evict popular content reducing the overall content distribution performance. NDN, MobilityFirst, and XIA are all susceptible to this attack.

Conti et al. discuss this attack in [102]. It is shown that with even limited adversarial resources, a highly effective cache pollution attack can be mounted. In fact, even small cache locality manipulation can cause a significant content distribution disruption [103]. It is also shown in [102] that launching pollution attacks on large networks is relatively easy, and smart adversaries reduce the effectiveness of proposed countermeasures.

Cache pollution attacks do not prevent users from retrieving the requested data. Instead, they negatively effect the performance of content distribution, and eliminate the benefits of in-network caching.

VIII. RESOLUTION SERVICES SECURITY

Resolution service is a fundamental part of the current Internet architecture. It maps human-readable names to routable network addresses. As mentioned above, new Internet architectures also require similar resolution services to operate. In this section we compare the security and privacy features of the various resolution services proposed in FIA projects. We exclude Nebula and XIA since they do not propose a new resolution service and only exploit the existing DNS/DNSSSEC.

We consider the following security features: trust, data origin authentication, data integrity, peer entity authentication, authorization and access control, accounting, data confidentiality and availability. We consciously exclude traffic flow confidentiality and anonymous communication since we believe they should be provided at the network layer.

A. Trust

DNSSEC introduces the notion of trust into DNS. It considers authoritative servers as trusted entities responsible of maintaining and securely providing the correct mapping between human-readable domain names and corresponding IP addresses. Recall that each DNSSEC server signs the resource records (name-to-IP mappings) of its respective domain. Trustworthiness of such servers is ensured by a chain-of-trust model that resembles the domains hierarchical organization. The top-level domain resides at the root of this chain.

Similar to DNSSEC, NDNS applies the same notion. Authoritative server are trusted entities and their trustworthiness is ensured by a similar chain-of-trust model.

GNRS, on the other hand, adopts a different approach. Every network is responsible of providing signed GUID-NA mappings. Thus, verifying these signatures ensures their validity. This also prevents (compromised) GNRS from manipulating GUID-NA mappings without being detected.

B. Data-origin authentication and data integrity

DNSSEC provides data-origin authentication and data integrity by requiring: (1) authoritative servers to sign each of their resource records, and (2) resolvers to verify the validity of these signatures and their corresponding public keys. This prevents adversaries from injecting bogus data into the DNS system.

Signing every response resource record is an expensive operation that authoritative server should not perform at run-time. Adversaries can abuse such costly operation to launch (D)DoS attacks against authoritative servers. To this end, resource record signatures should always be generated in advance. While this method can be easily applied in case resolvers asks for existing domain names, it does not work for a non-existing domain names. DNS uses the NXDOMAIN resource records to inform a resolver that the queried name does not exist. However, providing data-origin authentication and integrity for NXDOMAIN resource records can not be done by generating the signature in advance, because of the number of possible non-existing names is infinite. To solve this problem, DNSSEC introduces a new record type called the NextSEcure (NSEC) resource record. Specifically, assuming a canonical ordering of the domain names, a NSEC record contains two consecutive existing names in the canonical ordering, thus describing the gaps between them. Such records are signed and used as authenticated denial of existence for non-existing names. Since NSEC records contain existing names, their signatures can be calculated a priori.

In NDNS, query responses are carried in content object payloads, thus data-origin authentication and integrity is inherited from NDN. One difference between DNSSEC and NDNS resides in the granularity of these authentication and integrity guarantees. While DNSSEC can offer such security properties per individual resource record or resource record set, the fact that a NDNS record is carried in a content object can only guarantee the authentication and integrity of said record. Although this is a clear restriction in the flexibility and scalability of the protocol, it does not jeopardize its security.

In order to overcome DoS attacks due to requests for non-existing names, NDNS adopts methods similar to DNSSEC. In particular, NDNS servers can sign the gaps between existing names. Furthermore, Compagno et al. proposed in [104] the use of a Bloom filter to defeat the aforementioned DoS attacks. This, however, requires some changes in the NDN architecture as well as the introduction of a new content type.

GNRS also provides data-origin authentication and integrity by means of GUID-NA mapping signatures. The main difference between GNRS and DNSSEC is that the former does not assume that GNRS servers are trusted [60], while the latter requires all authoritative servers to be trusted.
C. Peer entity authentication

In DNS and DNSSEC there is no entity authentication between a resolver and a DNS server. Resolvers usually know the IP address of a DNS server which is used to initiate queries. Usually, such IP address is manually configured on the resolver or obtained through DHCP and considered valid. Using a TLS connection between resolvers and DNS servers can provide entity authentication [106], [107].

Authentication between DNS servers is obtained through Transaction signatures (TSIG) [57]. TSIG involves pairwise keys shared among DNS servers and used to secure dynamic updates, zone transfers and recursive queries. Moreover, in case of dynamic updates generated from DNS clients, a signature is used to authenticate that client and validate the update.

NDNS follows the same approach of DNS by not providing entity authentication. However, the fact that both NDNS users and servers are regular NDN consumers and producers, respectively, allows approaches similar to what is proposed in Section VII-C to be adopted. Furthermore, securing dynamic updates requires NDNS clients to have previously shared their certificate with the NDNS servers. Signing the updates will then authenticate them.

Unlike DNS and NDNS, GNRS authenticates every client issuing requests (query, update and delete) by retrieving the corresponding certificate, from NCS, and verifying the GUID authenticity. GNRS clients can ensure server authentication by performing similar steps, requesting certificates from NCS and verifying servers identities.

D. Authorization and access control

Both DNS/DNSSEC and NDNS do not provide any form of access control. All resource records are publicly available to every host in the network. However, authorization and access control is provided for dynamic updates.

GNRS does not follow the same trend and consider access control a crucial part of its design. Specifically, GNRS stores a set of access control policies along with GUID-NA mappings. Such policies regulate access to particular GNRS resources by specifying read and write permissions which blacklist and whitelist certain user GUIDs.

E. Accountability

DNS/DNSSEC guarantees accountability only for secure DNS dynamic updates [35]. This is because such requests must in fact be signed by their originators. Also, NDNS does not provide any mechanism for accountability. The fact that NDNS users and servers are consumers and producers allows the adoption of similar approaches described in Section VII-F.

GNRS uses a different approach and mandates GNRS clients to sign every request. By doing so, accountability is provided for all insert, update and query requests.

F. Data confidentiality

Neither DNS nor DNSSEC provide confidentiality. Queries and resource records are never encrypted by authoritative servers and are always exchanged in cleartext. One way of achieving confidentiality in DNS/DNSSEC is to establish a TLS session between resolvers and authoritative servers [106], [107].

Similarly, both NDNS and GNRS designs do not take confidentiality into consideration. Fortunately, similar approaches to using TLS channels can be adopted. This feature is important to provide private communication.

G. Availability

As a public available service, DNS is subject to (D)DoS attacks which jeopardize its availability. In particular, adversaries can flood authoritative servers with a large number of query requests to exhaust their resources. Although the use of DNS caching and redundancy servers reduce the effect of DDoS, a number of such attacks have been successfully directed against root and top-level DNS servers in past years [108]–[110]. Many solutions have been presented in past years that either: (1) require some changes in the DNS protocol [111]–[114], or (2) propose new resolution services [115], [116]. Nowadays, DNS uses a single approach that does not require any modification to its architecture, which is the adoption of “Anycast” [117]. In this case, a single DNS server is replicated in different geographically locations among several ASes. Therefore, routing protocols forward DNS requests to the nearest server that can satisfy them [118]. However, this approach can not achieve an efficient load balancing because it does not consider replica workloads and network traffic.

DNS resolvers (not implementing DNSSEC protocol) can be the target of cache poisoning attacks. This attack is similar, in concept, to content poisoning described in Section VII-J. In DNS cache poisoning attacks, the goal of the adversary is to inject spoofed responses (name-IP mappings) in the resolver caches [119]. Injecting false DNS responses can be achieved using a man-in-the-middle attack in which the adversary satisfies requests with false DNS responses [119]. The introduction of data-origin authentication in DNSSEC allows resolvers to verify the origin of data in DNS response, thus eliminating this attack.

NDNS follows the same hierarchical design of DNS. In principles NDNS authoritative servers seems to offer the same level of resilience to DDoS as DNS authoritative servers. Furthermore, NDNS envisions the use of a set of secondary servers to balance the workload, which was proven to be not effective. The same anycast approach used in DNS could be employed in NDNS. Such forwarding strategy must be implemented by NDN routers. Moreover, NDNS is susceptible to content poisoning attacks. Fortunately, the same countermeasures described in VII-J can be effective.

GNRS design appears to be more resilient to DDoS than DNS design. In fact, GNRS does not adopt a hierarchical structure, instead it distributes the GUID-NA mappings among a number of replicas using Distributed Hashtables (DHT) maintained by all the ASes in the Internet. This allows GNRS to easily scale and distribute a DDoS attack.

[*The use of secure dynamic updates involving asymmetric encryption increases the effect of the attack.*]
IX. LESSONS LEARNED AND FUTURE DIRECTIONS

In this section we summarize all the security and privacy features provided by the network layer of the FIA architectures and their corresponding resolution services. We also highlight the missing features and delineate a direction for future work on security and privacy in both network layer and resolution services.

A. Network Layer

The strong requirement to include security and privacy by design seems to have been only partially reached by FIA funded projects. Table I summarizes the security and privacy features provided by each architecture.

**Nebula.** At its current state, Nebula includes trust, data origin authentication, peer entity authentication, data integrity, authorization and access control, accountability, and availability features. All of them are provided between senders and routers implementing ICING, expect for peer entity authentication that is guaranteed between senders and consent servers during the retrieval of the PoCs. With respect to IP and IPsec. Nebula certainly increases the security of intra-domain communication. However, it lacks to consider inter-domain and end-to-end communication security. While current approaches can be adopted, e.g., establishing an IPsec-like secure communication between two end hosts, researcher should investigate these two directions further.

Availability in Nebula is provided by path verification mechanism which prevents any adversary from sending unrequested data to perform bandwidth depletion attacks. However, ICING nodes and consent servers could be the target of a DoS attack, due to the heavy use of cryptographic operations. Consent servers can be another target for DoS attacks. In particular, an adversary can flood a server with an abnormal amount of request. If the target server controls a large number of routers, the attack can effectively disable all of them. We believe that such attack deserves further investigation.

Other analyzed features, i.e., data confidentiality, traffic flow confidentiality and anonymous communication, are not currently provided. The first two can be easily implemented by applying the same well-known technique used in IP/IPsec. However, Nebula should investigate and make these features available by design before any adoption in the real world. Furthermore, anonymous communications contradict with the current design of ICING which requires path establishment for each communication. Therefore, further investigation is required by the research community to provide anonymity in Nebula.

**NDN.** This architecture replaces hosts as primary entity in the network with content. This affect the security features provided at network layer by focusing them on content rather than end-hosts. Currently, NDN provides: trust, data origin authentication, data integrity and data confidentiality. Security features like peer entity authentication and accountability are available only when derived from data origin authentication for both interest and content. Ubiquitous caching further complicates achieving these two features. In fact, when a consumer obtains a content from an intermediate router’s cache, there is currently no way to provide peer entity authentication between the consumer and the router providing the content. Similarly, accountability for content refers to the producer generating that content and not to any intermediate router serving it from its cache.

Availability is a security feature in which NDN provides some improvements as compared to IP/IPsec but at the same time it opens the door for new types of attacks. While the pull model communication prevents any adversary from flooding a host with non-requested content, adversaries can exhaust router states (i.e., PIT and CS), decreasing the performance of a network. Even through several countermeasures have been proposed, none of them has been chosen and implemented as part of the architecture.

The remaining security features: authorization and access control, traffic flow confidentiality and anonymous communication are not provided by the network layer. Even if ACL can be implemented, NDN chooses to delegate access control to the application layer by encrypting content and distributing the decryption keys only to authorized consumers. Traffic flow confidentiality and anonymous communication are not available but existing approaches designed for IP and IPsec can be applied without any modification of the NDN architecture.

**MobilityFirst.** The security features provided by this architecture combine in principle the end-to-end hosts approach and the content-based approach of IP/IPsec and NDN, respectively. However, at the current state, MobilityFirst seems to fully provide only few security features, i.e., trust, authorization and access control. The adoption of self-certifying names to address hosts facilitates the implementation of data origin authentication, peer entity authentication, and accountability. Peer entity authentication can be achieved involving a simple challenge-response protocol between the two peers. While this guarantees end-to-end accountability, it is not enough to provide network accountability. In order to achieve that, edge routers should prevent address spoofing.

Data integrity and data confidentiality are currently not provided at network layer and it is not clear if MobilityFirst approach is to let applications deal with them. Traffic flow confidentiality and anonymous communication are also not provided. Existing approaches designed for IP/IPsec can be easily imported. However, we encourage a deeper investigation in order to design new techniques able to exploit the peculiarities of the new architecture.

The current design of MobilityFirst can help against content poisoning attacks (i.e., the use of SCN prevents a benign user from receiving fake content). Meanwhile, MobilityFirst does not seem to have fully considered other network attacks such as bandwidth depletion attacks and cache pollution attacks. Existing solutions can be applied to mitigate these problems. We believe a further investigation is worth being conducted in order to provide some new and architecture-related countermeasures.

**XIA.** The main goal of this architecture is to support communication between multiple and different principals. XIA security approach extends, de-facto, the MobilityFirst approach...
in which security is provided and designed for two principals: content and hosts. XIA does not limit the number of principals but instead provides the freedom to design new ones. To this end, XIA security is based on each principal intrinsic security feature.

The current state of XIA offers the same security and privacy features as MobilityFirst. This is due to their similar approach in addressing principals using SCNs.

B. Resolution Services

Resolution services are of a primary importance in both the current Internet architecture and the new FIA proposals. In Nebula, the resolution service is used by the NVENT to perform path discovery. In NDN, the same service provides the mapping between namespaces and the corresponding security information. In MobilityFirst, the resolution service is actively involved in any communication guaranteeing the binding between GUIDs and NAs. Finally, XIA’s DNS-based resolution service is used for the address/path resolution.

Although all architectures require a resolution service, only NDN and MobilityFirst are actually investigating their own proposal. In Table I we summarize the security and privacy features provided by NDNs and GNRS.

NDNS. NDNS design reflects in many part the design of DNS without bringing too much novelty. NDNS involves the same notion of trust of DNSSEC in which servers are trusted entities. Moreover, NDNS queries and responses provide: data origin authentication, data integrity, accountability only in case of dynamic updates, and availability. The last feature is provided by server replication. However, while in DNSSEC the “Anycast” technique is used to choose the closes server to the resolver, in NDNS the network must be aware of all servers and implement specific forwarding strategies to balance the requests among them, which adds more complexities.

Peer entity authentication, authorization and access control, and data confidentiality are not provided. We believe that NDNS deserves further investigation to provide better availability, as well as the missing security features.

GNRS. The GNRS design is completely different from the current DNS and DNSSEC. In fact MobilityFirst assumes a flat name structure which forces GNRS to assume a flat structure for its servers. This different organization has some side effects on the provided security features: servers are not assumed to be trusted entities and, data origin authentication is provided by the owner of the GUID and not by servers. GNRS also introduces authorization and access control of its stored information and provides accountability and peer entity authentication in every query and response. Finally, GNRS is more robust to DoS attacks than DNS. First, compromising one server does not affect others. Second, GNRS is designed to easily adapt to network changes and to balance GUID-NA mapping among many replicas based on requests locality.

We believe that GNRS introduces good security improvement with respect to the current DNS and DNSSEC. However, the only missing feature is data confidentiality.

X. Conclusion

Despite the unquestionable success of the current IP-based Internet architecture, the lack of security considerations in its design lead to many severe security breaches and privacy leakages for many years. One goal of future Internet architectures is to include security and privacy features that are missing in the design of the current Internet.

In this survey, we provided a thorough analysis of security and privacy features currently supported by the network layer of four architectures involved in the FIA program: Nebula, NDN, MobilityFirst and XIA. We focused on features we believe should be available at the network layer in order to achieve secure and private communication. We considered IP/IPsec as a point of reference in our analysis. Moreover, we included resolution services provided by the different architectures since each one can not abstain from relying on such a service.

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TABLE II

| Security and Privacy Features | Resolution Services |
|-------------------------------|---------------------|
|                               | NDNS | GNRS |
| Trust                         | ✓    | ✓    |
| Data Origin Authentication    | ✓    | ✓    |
| Peer entity Authentication    | ✖    | ✓    |
| Data Integrity                | ✓    | ✓    |
| Authorization and Access Control | ✖    | ✓    |
| Accountability                | ✖    | ✓    |
| Data Confidentiality          | ✖    | ✓    |
| Availability                  | ✖    | ✓    |

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