A Note on Advancing Scalable Routing in Named Data Networking,

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Abstract*—The vision of Information-Centric Networking (ICN) represents a paradigm shift in network communication, moving away from the traditional node-centric IP model to a data-centric approach known as Named Data Networking (NDN). This paper aims to explore the implications of this architectural transformation on network routing and forwarding, highlighting both the changes and continuities in this context. To begin, we provide clear definitions for several fundamental networking terms, such as addresses, locators, and locations. Subsequently, we emphasize that, concerning the scalability of network routing, the fundamental solution strategies employed in scaling IP network routing can be equally applicable to NDN. Furthermore, we delve into several distinctive NDN forwarding scalability solutions that are made possible by the practice of naming data and NDN's Stateful forwarding plane. We argue that the concept of rendezvousing on data introduces a new and innovative dimension to the solution space for addressing network scalability challenges.

Keywords: Naming, ICN, NDN, IP, Forwarding.

1.INTRODUCTION

In the realm of network architecture design, two fundamental questions revolve around naming—specifically, the type of identifier(s) a packet carries—and forwarding—how a packet is directed through the network based on these chosen identifiers. In the context of today's IP networks, these questions are well-established. Packets typically carry source and destination IP addresses, and routers employ routing protocols to configure forwarding tables. This enables packets to be forwarded to their destination nodes in a stateless manner.

Information-Centric Networking (ICN), adopts a data-centric communication model that shifts the focus from "where" to "what." Named Data Networking (NDN), as exemplified in its design[1], is a prime example of this approach. In NDN, each packet carries a data name, and communication revolves around retrieving desired data based on application-layer names. In stark contrast to IP's point-to-point packet delivery based on addresses, in an NDN network, each piece of data is uniquely named and signed by its producer. It is encapsulated in a network layer Data packet. To retrieve data, a consumer sends an Interest packet containing the name of the desired data. When forwarding an Interest packet, each forwarding node has various options, including using a forwarding table, forwarding to one or multiple next hops, or employing methods like random walk or flooding to progress the Interest toward the potential location of the requested data. Importantly, each forwarder retains information about the interface through which an Interest arrived, allowing Data packets to follow these "breadcrumb trails" and reach requesting consumers in a hop-by-hop manner. This reflects NDN's reliance on a stateful forwarding plane, a significant departure from IP's stateless approach. In terms of naming and forwarding, the most substantial disparities between IP and NDN are twofold: the focus on naming data rather than endpoints and the shift from a stateless to a stateful forwarding plane. These fundamental distinctions require a reevaluation of fundamental principles.

This paper serves a dual purpose. First, due to the pronounced difference in what is named in IP and ICN, there has been confusion in recent literature on ICN concerning the basic concepts of naming and forwarding. This necessitates clarification. Second, naming and forwarding are critical elements in addressing network routing scalability, multihoming, and mobility support, challenges that have persisted in networking for a considerable time. Addressing these challenges in the context of ICN demands a reconsideration of the solution space.

The primary contribution of this paper is a clear delineation of the impact of network architectures on the solution space for routing and forwarding scalability. Transitioning from IP's node-centric data delivery to ICN's data-centric retrieval, we elucidate what changes and what remains the same—the solution approaches that are architecture-dependent or architecture-independent. We start by clarifying the core concepts of address, locator, and location, emphasizing why they remain consistent in terms of network routing and forwarding scalability issues during the shift from IP to NDN. Additionally, we explain why the fundamental approaches to routing scalability in IP networks are also relevant in NDN routing. Subsequently, we elucidate the elements that do change in the solution space and present several existing solutions for NDN forwarding scalability. These solutions are made possible by naming data and leveraging NDN's stateful forwarding plane. We also highlight how rendezvousing on named data introduces a fresh dimension to the solution space.

II. NAME, ADDRESS, IDENTIFIER AND LOCATOR

In this section, we initiate a brief comparison between IP and NDN. Subsequently, we aim to provide clarity on the fundamental concepts of name, address, identifier, and locator, which remain architecture-independent. Notably, we emphasize that identifiers transform into locators when they are introduced into a network's routing plane. This introduction serves to establish the reachability to the identified entities, whether they are nodes or data objects. In both node-centric and data-centric networking paradigms, naming serves the purpose of identification (nodes in IP and data objects in NDN), while forwarding pertains to achieving reachability.

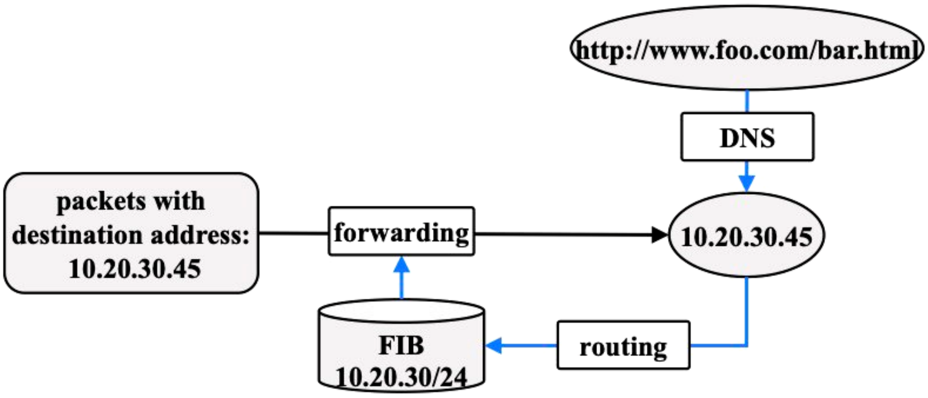


Fig. 1. A web-browsing example in IP

A. Network Layer Naming

Let's examine a common scenario in the context of the Internet: a web browser's task of fetching a web page, denoted as W, from a website. As depicted in Figure 1, executing this task within an IP network entails at least three key processes: 1) Name Resolution: Since the web page W is identified by a URL containing a name, while the network can only deliver packets to a specific IP address, the Domain Name System (DNS) comes into play to bridge the naming gap between the application and network layers. The browser initiates a DNS query to resolve W's name into an IP address, denoted as WA. 2) Routing: To enable the delivery of packets to the destination with IP address WA, an IP prefix covering WA must be announced into the network's routing plane. This announcement triggers the establishment of an entry, such as {IP prefix → outgoing interface}, in the Forwarding Information Bases (FIBs) of every router. 3) Forwarding: Once packets carrying the IP address WA are in transit, they are forwarded to the website based on the predefined FIBs, ensuring their successful delivery. This process illustrates how IP networks handle the task of delivering content from a source to a destination, relying on IP addresses for routing and forwarding. In the subsequent sections, we will explore how NDN, with its data-centric approach and data names, differs in handling similar scenarios.

Figure 2 provides an illustration of how the same web-browsing task is executed within an NDN network. In this context, the name included in the web page W's URL is directly employed for both network layer routing and forwarding, eliminating the need for a name-to-address resolution process. The other two processes can be conducted in a manner similar to those in IP: a name prefix encompassing the data name is introduced into the routing plane. This action leads to the establishment of an entry in router Forwarding Information Bases (FIBs), denoted as {name prefix → outgoing interface}. Subsequently, an Interest packet is generated, carrying the data name, and serves as a request for the webpage. This Interest packet can then be forwarded toward the website, following the predefined FIBs. In node-centric network naming using addresses, the scope of identification is often limited to a device or an interface at the network layer. Consequently, contents and services must be named at the application layer. This necessitates the presence of a namespace mapping system, such as the Domain Name System (DNS), to bridge the gap between these distinct namespaces. In contrast, an NDN network directly utilizes the application layer namespace at the network layer. Depending on the requirements of specific applications, an NDN name may take the form of a structured string resembling a URL or a flat bit/byte/numeric string. NDN eliminates the constraint imposed by IP, where network layer identifiers are primarily used for naming communication endpoints. In the context of networking, NDN names have the flexibility to designate a wide range of entities, including endpoints, interfaces, commands for controlling devices (e.g., turning on lights), and processing functions. This versatility extends beyond data objects from sources such as movies or books.

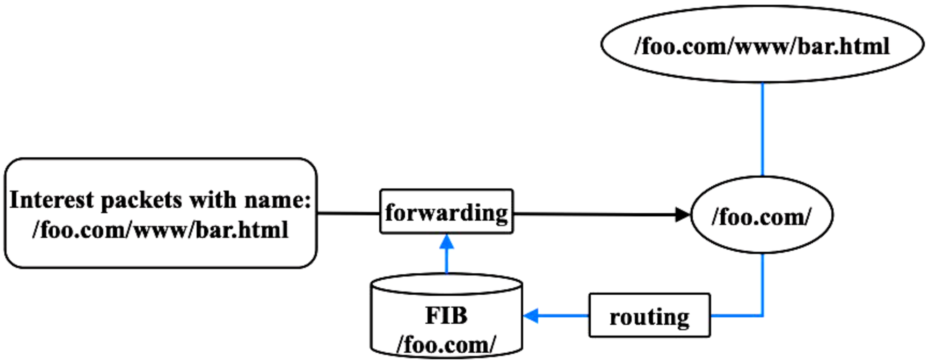


Fig. 2. A web-browsing example in NDN

B. **Clarification on Concepts**

From a routing algorithm perspective, IP address prefixes and data name prefixes share a fundamental similarity. They both serve to identify forwarding directions within a network's topology, which can be viewed as a graph-theoretic abstraction. The key difference lies in the potential length of these prefixes. Once a prefix, whether it's an IP address prefix or an NDN name prefix, is introduced into Forwarding Information Bases (FIBs) through a routing protocol, network forwarders can utilize these established FIBs to match the addresses or names carried in the packets that need to be forwarded. Notably, a well-known link-state routing protocol, IS-IS, is designed as a network-layer-independent protocol [2].

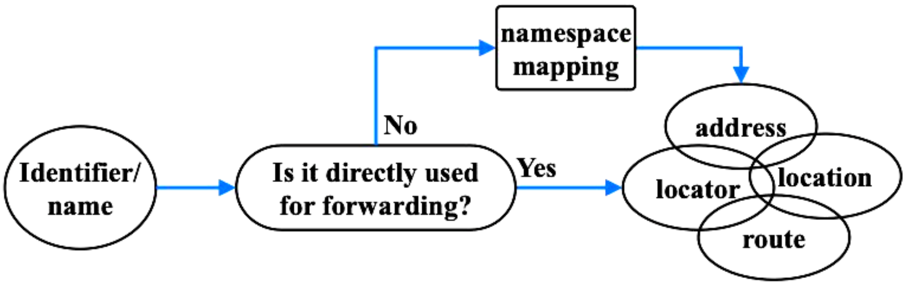


Fig. 3. Name/address-related concepts at network layer

In essence, both types of prefixes, whether they pertain to IP or NDN, serve as routing directives and enable the efficient forwarding of packets within the network. The distinction lies in the specific identifier used (IP addresses in IP networks and data names in NDN) and the potential differences in prefix length, but the underlying routing principles remain consistent.

In light of the previous explanation, we can provide clarification on some interconnected concepts: identifier, name, address, locator, location, and route. These concepts are depicted in Figure 3. All the terms mentioned can be regarded as identifiers, as they serve the purpose of identifying something. When an identifier or name is directly employed for forwarding and is set in Forwarding Information Bases (FIBs), it also functions as a locator, address, or location for the entity it references. In the case of IP, an IP address serves as both an identifier for an interface and a locator within FIBs. Similarly, in NDN, a data name also serves as a locator for the data if its name prefix is included in FIBs. There's no fundamental difference between the concepts of name and address in this context, aside from their varying lengths. Notably, nowadays, IP address blocks can be globally traded like other types of resources, and IP addresses do not inherently signify specific fixed locations, whether physical or topological. Therefore, we can clarify that an IP address is essentially a constrained name.In practice, not all identifiers are directly used for forwarding, primarily due to concerns about routing scalability. The global Internet faces scalability challenges when there are too many identifiers introduced into the routing system or when the reachability of these identifiers exhibits high dynamics. Routing scalability has been a central research challenge since the early days of networking, and the demands for multihoming and mobility support in recent times have exacerbated the problem. Multihoming leads to prefix disaggregation, while mobility introduces higher dynamics. A fundamental approach to addressing routing scalability is to implement a mapping system that can map a non-routable identifier to a routable one or convert a highly mobile prefix into a stable one. This approach transforms the dynamics of prefixes into frequent updates within the mapping system without disrupting the overall routing system. This topic will be further explored in the next section. With this understanding, we can now discuss the concept of "location-independence." In a previous work [3], NDN was described as "location-independent," allowing communication using fixed names without concern for changing network locations. It's important to note that no architecture can be unequivocally labeled as either location-independent or location-dependent. The classification depends on the dynamics of the entities being named and their relationship to the routing system. For instance, a piece of data in NDN can be location-dependent if it remains stationary and its name prefix is introduced into the network routing system to establish an entry in FIBs. On the other hand, a mobile device in an IP network can be considered location-independent if it injects its address into the routing system, as exemplified by Connexion [4]. Furthermore, it's crucial to emphasize that an identifier should remain constant as long as it identifies the same entity. In NDN, the same data with the same name can be moved to different locations and retrieved from those locations. The key technical challenge is not solely about location (in)dependence but rather how to establish the reachability to data in a scalable manner.

III. IP ROUTING SCALABILITY ISSUES AND SOLUTIONS

The preceding section has clarified that whether it's an IP address or a data name, an identifier serves as a locator when it is directly introduced into network routing. When it comes to routing announcements, both IP and NDN networks face similar challenges regarding routing scalability. In this section, we will briefly revisit prior work on IP routing scalability and argue that the fundamental solutions devised for IP are equally applicable to NDN.

A 2007 IAB workshop report [5] synthesized research findings on network routing scalability. The size of routing tables at the Default-Free Zone (DFZ) has been consistently expanding at a super-linear rate, posing a potential threat to outstrip the hardware capabilities projected by Moore's Law. The report identified three primary factors contributing to the growth in the size of DFZ routing tables: the absence of renumbering after changes in topological connectivities, multihoming, and traffic engineering. Regarding the guiding principle for making routing scalable, Yakov Rekhter made a significant observation, often referred to as "Rekhter's Law" [5]: Given that the global Internet topology is shaped by both technological and economic relationships among Internet service providers, it is impractical to have topology strictly adhere to addressing. Yet, all three identified factors in the report result from addressing not closely aligning with topology, creating a dilemma. Recognizing that Rekhter's Law is architecture-independent, it's evident that both IP and NDN can encounter the same dilemma in addressing routing scalability.

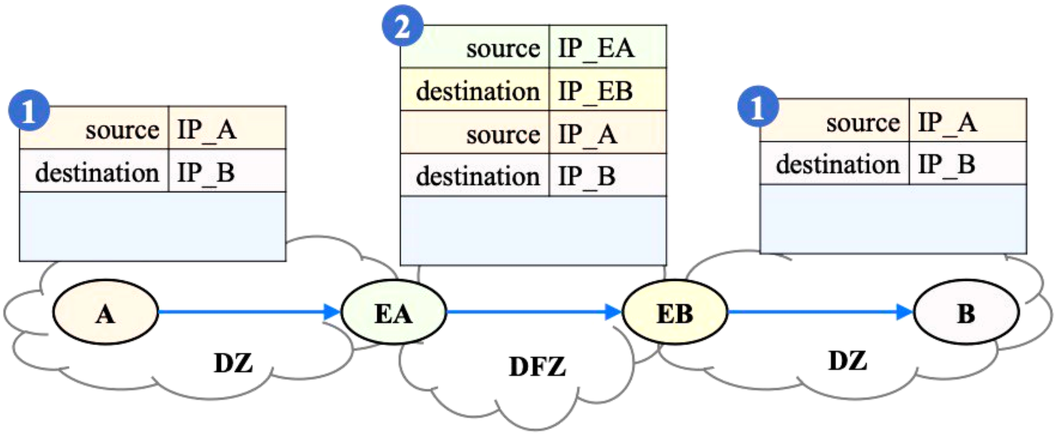
To address this challenge in IP networks, two main approaches were proposed. The first approach [6]-[8], known as locator/identifier separation, aims to provide a location-independent identifier for each host. This is believed to enable the reorganization of IP address allocations to align with network topology. A mapping system is required to link location-independent host identifiers to location-specific addresses.

The second approach [9]-[12] attempts to separate provider and customer address space by assigning unique identifiers to customer networks and mapping these identifiers to the connected provider networks. This separation decouples the transit core from edge networks, eliminating the need for renumbering when customers change providers and simplifying multi-homing.

As concluded in [13], the primary distinction between these two approaches lies in the fact that locator/ID separation necessitates substantial architectural changes without strong incentives, while address space separation aligns with the natural need for evolution, driven by the growth and power of user networks that do not conform to the addressing constraints imposed by transit providers. Given two separated namespaces, whether locator/ID or transit/user address, it's observed that all routing scalability solutions attempt to manage routing table size by mapping non-routable names (those that aren't included in routing announcements) to routable names (those that are announced to the routing plane).

We believe that the aforementioned findings and approaches are also applicable to NDN. To scale routing in NDN, one must decide whether a given name (prefix) should be announced in the routing system and, if not, determine how to map this non-routable name to directly routed names. It's worth noting that solutions for mobility support can also serve as routing scalability solutions [14]. In the context of IP, examples include Mobile IP [15], which implements locator/identifier separation, and Cellular IP [16], which uses per-hop tracing to update the forwarding path from a reachable anchor to a mobile node M, making M reachable without adding M to Forwarding Information Bases (FIBs). This Cellular IP work suggests a fundamentally different approach to scaling routing: addressing dynamics by updating local forwarding states.

In summary, the fundamental approaches to routing scalability developed for node-centric networks are equally applicable to scaling routing in data-centric networks.



(a) map-n-encap scheme

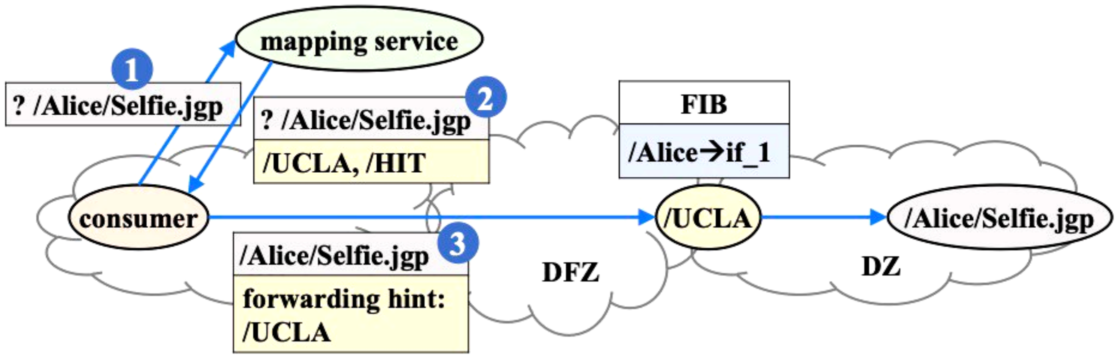


Fig. 4. Mapping-based solutions in IP and NDN

The routing scalability problem exists in both architectures, and the guiding principles for solutions are architecture-independent.

IV. WHAT CHANGES

In this section, we will pinpoint the factors associated with routing scalability that undergo changes during the architectural shift from a node-centric to a data-centric model. Additionally, we will discuss several novel routing scalability solutions facilitated by the practice of naming data and NDN's stateful forwarding plane. As discussed in a previous work [17], the stateful forwarding plane plays a crucial role in liberating routing protocols from short-term fluctuations, significantly enhancing their scalability. This enables NDN to employ routing protocols that were previously considered impractical for real networks, such as hyperbolic routing [18]. Here, we introduce some routing-independent solutions for scalability.

A. **Mapping-Based Solutions:** One category of routing scalability solutions involves the use of a mapping system to link identifiers that are not included in routing announcements to those that are announced globally in the routing system. This approach allows the routing plane to handle only a fraction of the entire identifier space, focusing on stable and aggregatable portions. This, in turn, leads to a reduction in the Forwarding Information Base (FIB) size and fewer routing updates. An early proposal for a mapping-based solution in IP networks, known as map-n-encap [9], is depicted in Figure 4 (a). When Packet-1 reaches a Default Free Zone (DFZ) router EA, the destination address is mapped to a DFZ egress router address IP EB. Subsequently, the original packet is encapsulated to create Packet-2, featuring a destination address corresponding to the egress router. Upon receiving Packet-2, the egress router EB removes the encapsulating header and forwards the original Packet-1 to the destination.

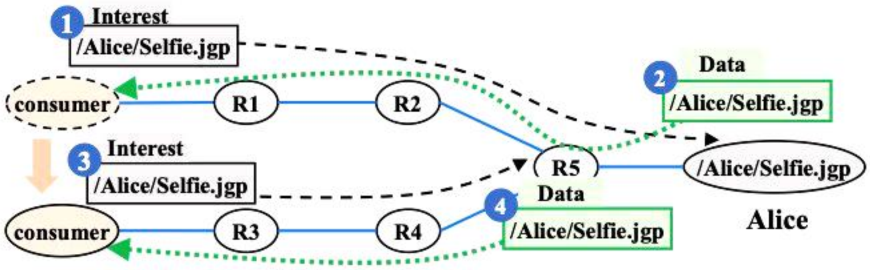
SNAMP [19] is a mapping-based solution proposed for NDN, as illustrated in Figure 4 (b). A consumer can obtain the whereabouts of the desired data, i.e., the data locator, from a mapping service. However, instead of encapsulating the Interest packet (which would alter the name carried in the Interest), SNAMP allows an Interest packet to carry the locator as a forwarding hint. Unlike an IP packet, which typically carries only a single identifier, an Interest packet (Packet-3) can encompass both the "what" (data name) and the "where" (forwarding hint) needed to retrieve the data. While routers forward the Interest toward the location where the data is available based on the forwarding hint, the data name remains visible to intermediate routers. This visibility allows these routers to potentially match the Interest to cached data, even before it reaches the "where" location. Moreover, an Interest can be resent carrying different forwarding hints, providing data consumers with flexibility in their retrieval process.

B. Tracing-Based Solutions

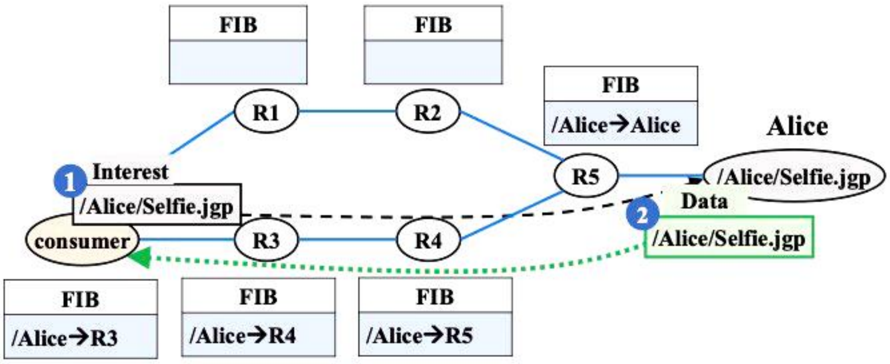
Tracing-based solutions for routing scalability can take full advantage of NDN's stateful forwarding plane, which allows the creation of a "breadcrumb trail" leading to a data producer. In NDN forwarding, when a router receives an Interest and does not possess the requested data, the router records the Interest along with its incoming interface in the Pending Interest Table (PIT) and subsequently forwards it based on the Forwarding Information Base (FIB). The state information stored in the PIT of each router that the Interest traverses establishes a reverse path, akin to a "breadcrumb trail," for the requested data's return journey. While similar approaches were initially introduced for IP multicast [20] and IP mobility [16] support, the concept of creating state to form a "breadcrumb trail" contradicts IP's stateless data plane, which is why such solutions are not widely deployed in IP networks. One crucial aspect of the stateful forwarding plane is its ability to cater to consumers of Forwarding Information Bases (FIBs). Because Data packets are returned by following the Interest packet's reverse path back to the consumer, mobility for consumers is natively supported. As depicted in Figure 5 (a), when a consumer relocates before receiving Data packet (Packet 2), the consumer re-issues an unsatisfied Interest (Packet 3), thereby creating or updating the reverse path to its current location. Self-learning routing [21] harnesses the stateful forwarding plane to establish consumer-initiated traces leading to the producer. As shown in Figure 5 (b), in the absence of a matching FIB entry, an Interest packet (Packet 1) can be either flooded or randomly unicast, eventually reaching the producer. Along the path of the returning Data packet (Packet 2) to the consumer, each router generates a FIB entry for the corresponding data name prefix, directing it to the incoming interface of the Data packet.

KITE [22] represents a tracing-based solution tailored for producer mobility. KITE enables data retrieval from a mobile producer by configuring a path in FIBs from a stationary rendezvous server (RV) to the mobile producer. As illustrated in Figure 5 (c), the RV issues a routing announcement for a shorter data name prefix ("/UCLA"). The producer, Alice, initiates a signed Trace Interest (TI) (Packet 1) to the RV. The RV validates the TI and responds with a signed Trace Data (TD) (Packet 2), which subsequently makes its way back to the mobile producer. Upon receiving a TD, intermediate routers (RV and R5) generate or update FIB entries for the data name prefix ("/UCLA/Alice"), directing them to the incoming interfaces of the TI. A consumer's Interest (Packet 3) is then forwarded toward the RV to reach the producer. Notably, the data name prefix ("/UCLA/Alice") only appears in FIBs along the trace, thereby alleviating the routing plane's burden of tracking mobile prefixes.

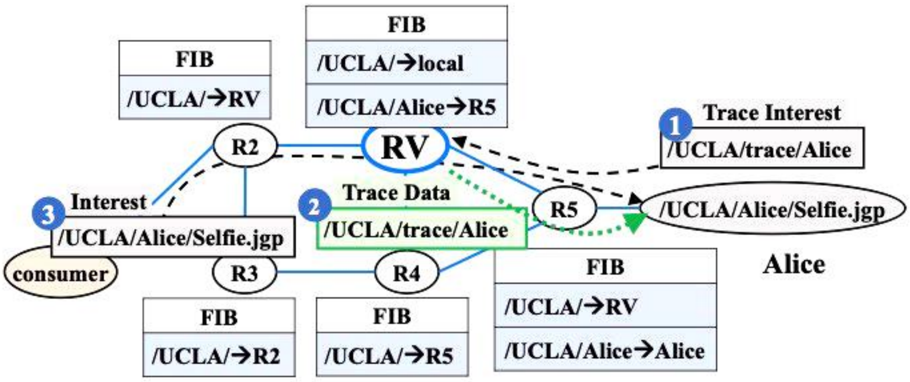
B. **Data Rendezvous:** Data-centric networking introduces an entirely new dimension to routing scalability by emphasizing the retrieval of named data, which leads to the concept of data rendezvous. Data rendezvous is founded on the idea that Interests merely need to converge with data at a rendezvous point, which does not necessarily have to be the original data producer. In-network caching, as depicted in Figure 6 (e), epitomizes this concept: popular data is automatically cached away from its producer and disseminated to multiple router caches that are in proximity to potential consumers. In traditional node-centric networks, the network layer can solely identify nodes, and application data caching can only be implemented at the application layer.



(a) consumer mobility



(b) self-learning routing



(c) KITE

Fig. 5. Tracing-based solutions in NDN

Data rendezvous in NDN can be achieved by relocating data generate by mobile devices to stationary servers that are already routable. These servers are referred to as "data depots," as illustrated in Figure 6 (f). A data depot may resemble a home agent in Mobile IP or the RV server in KITE, with the distinction that a data depot assumes full responsibility for hosting the data rather than merely aiding in Interest forwarding. Once user data is uploaded to the depot, it becomes easily accessible to others for retrieval. A data depot may appear similar to a conventional mapping server, with the key distinction being that it already possesses the desired data. Contemporary cloud storage services, such as Dropbox and Google Drive, can conceptually fulfill the role of a data depot. However, they typically require users to connect to specific nodes first before accessing their data.

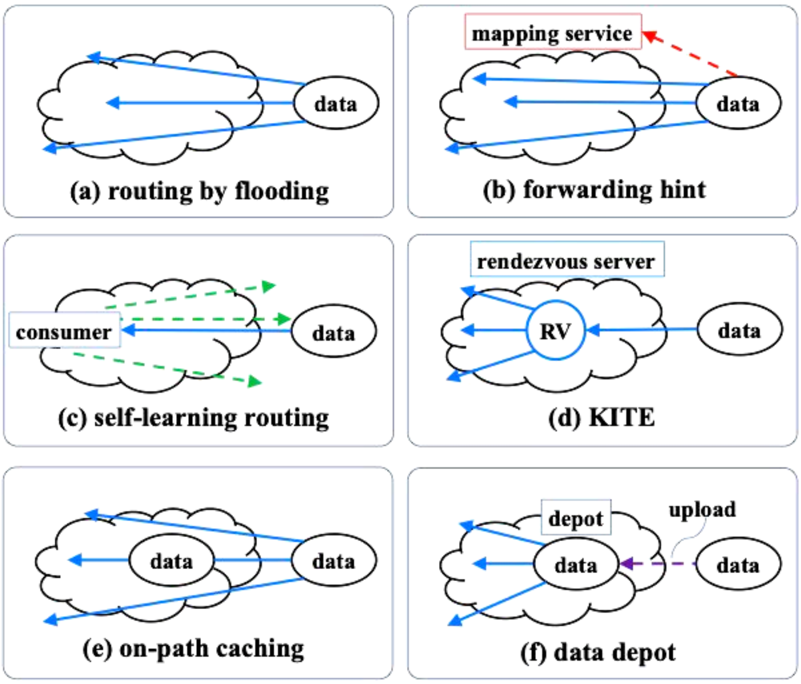


Fig. 6. Different solutions to achieve the reachability

NDN's inherent support for consumer mobility and tracing-based mechanisms for producer mobility render it a mobility-friendly networking paradigm. If all data generated by personal devices and Internet-of-Things sensors is aggregated into data depots, then device-specific prefixes wouldn't need to be injected into the routing plane. Nonetheless, there is a cost associated with getting data into data depots. Therefore, an important research question arises concerning different data rendezvous design choices, including a) collecting data availability without physically moving the data, b) transferring data to edge storage [24], and c) relocating data to a data depot.

In summary, network forwarding relies on the availability of reachability information for all identifiers. Figure 6 illustrates how the solutions outlined above accomplish this objective, highlighting the transformative impact introduced by data-centric networking.

V. RELATED WORK

In the early days of networking, Shoch [25] introduced key terminologies: a "name" identifies "what," an "address" identifies "where," and a "route" identifies "how to get there." Saltzer [26] further categorized four types of network destinations: services and users, nodes, network attachment points, and paths. Saltzer's framework unified Shoch's definitions by relating a "name" in Shoch's context to the name of a service meaningful to humans, with the "address" of that service representing the name of the node where the service is hosted. A "route" to the "address" essentially corresponds to a path leading to a network attachment point on that node. Day [27] extended this conceptual model by using abstraction and binding to represent node-centric networking. He contended that, in principle, communication occurs between entities at the same layer and emphasized that the root issue of IP routing scalability arises from the absence of a layer that identifies hosts or nodes. In this paper, we emphasize that when a name is directly employed in routing or forwarding, it functions as the locator for the entity it references.

In exploring the design space of mobility support, Zave and Rexford [28] introduced a geomorphic model comprising multiple layers at varying levels. DRM (Dynamic-routing Mobility) retains an entity's identity even as its location (network layer attachment) changes by adjusting intra-layer states, such as routes represented as mappings from destinations to next hops. In contrast, SLM (Session-Location Mobility) modifies the identity of a relocated entity to align with the location change while preserving the entity's identity at a higher layer through inter-layer mappings. We consider tracing, built on NDN's stateful data plane, as a novel approach within the DRM category, where forwarding hints empower packets to carry both data names and locators. Additionally, data rendezvous represents a fresh solution that goes beyond SLM and DRM. For a more comprehensive examination of mobility support in NDN, readers can refer to [23].

Gao et al. [3] differentiated three "puristic" approaches to offer location independence: "indirection routing," "name-to-address resolution," and "name-based routing." Their paper provided a quantitative comparison of these approaches in terms of path stretch and update cost within scenarios involving device and content mobility. Chaganti et al. [29] followed in the footsteps of [3] and assessed the three approaches across various parameterized mobility models. Notably, in our categorization, both "indirection routing" and "name-to-address resolution" schemes fall under the mapping-based approaches, as they both require a separate locator to represent the device or content's current location.

The term "location-independent architecture" warrants further elucidation. While proposed network architectures like NDN [1] and MobilityFirst [30] each embody a distinct networking paradigm, NDN uses application names at the network layer, whereas MobilityFirst distinctly separates application namespaces from the network address namespace. NDN's data-centric model inspires a novel approach to achieving location-independent communication, which revolves around data availability rather than node or channel availability.

VI. CONCLUSIONS

We hold the belief that the future of networking hinges on the recognition of the appropriate communication abstraction. Data-Centric networking introduces a fundamentally distinct communication model compared to today's Node-centric IP networking. Contrary to common concerns about NDN's routing scalability, NDN paves the way for entirely new and more efficient methods to implement existing solutions, such as namespace separation and mapping. Furthermore, it expands the solution space by enabling tracing and data rendezvous, opening up innovative possibilities for network design and operation.

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