Bootstrapping Real-world Deployment of Future Internet Architectures

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Abstract
The past decade has seen many proposals for future Internet architectures. Most of these proposals require substantial changes to the current networking infrastructure and end-user devices, resulting in a failure to move from theory to real-world deployment. This paper describes one possible strategy for bootstrapping the initial deployment of future Internet architectures by focusing on providing high availability as an incentive for early adopters. Through large-scale simulation and real-world implementation, we show that with only a small number of adopting ISPs, customers can obtain high availability guarantees. We discuss design, implementation, and evaluation of an availability device that allows customers to bridge into the future Internet architecture without modifications to their existing infrastructure.

1. INTRODUCTION

To be successful in their deployment, designers of new technologies must not only solve technical issues (e.g., compatibility, efficiency, etc.), but must also offer convincing incentives for users to invest time and money to adopt the technology. Without proper incentives, achieving substantial real-world deployment is likely a futile effort.

The deployment of new Internet architectures is especially challenging given the millions of hours of effort that have gone into building the networks these new architectures are designed to replace. Over the past two decades, a number of new ideas that provide strong technical advantages over existing networks and protocols (e.g., mobile IP [21] and IP multicast [5]) have been proposed. However, they have failed to gain mainstream adoption. The resistance to change may be justified, since sizeable financial investments and millions of hours spent on training make embracing potentially disruptive changes a less than ideal proposition for incumbents.

Future Internet Architectures (FIAs) aim to solve many problems with current-generation networks (e.g., security, availability, and scalability). To solve these issues, FIAs suggest using radically different paradigms. For example, NDN [12] provides efficient data delivery by treating data (rather than the end-points) as a first-class citizen on the network; MobilityFirst [25] designs a mobility-centric network; and XIA [8] delivers a flexible means of evolving the Internet’s core; and SCION [14] and NIRA [22] focus on making the Internet more resilient to failures. Despite the appealing benefits offered by these architectures, they have yet to gain mainstream adoption.

In this paper we present a case study on how to bootstrap deployment of FIAs by focusing on how to convince early adopters. We demonstrate that deployment of a new Internet architecture can provide tangible benefits to early adopters while requiring minimal changes to existing infrastructure during the initial stage of deployment. Our goal is to present a feasible adoption plan to gradually (and without friction) gain traction. Thus, instead of proposing a generic one-size-fits-all plan (i.e., attempting to convince manufacturers, ISPs, developers, and end users that they should immediately deploy a particular FIA), we focus on providing a single tangible benefit to early adopters: increased network availability. For this goal, we propose using FIAs as fallback (backup) networks when specific quality of service metrics are not met by current Internet paths. We note, however, that we focus exclusively on initial deployment. Later steps will need other incentives since network availability alone may be insufficient to motivate wide-scale deployment.

Based on simulations, real-world implementation, and evaluation, we show that with only a small number of deploying nodes, new Internet architectures, such as NIRA and SCION, can transparently improve network availability while introducing negligible performance overhead once deployed. Our results provide evidence that the seemingly impossible task of deploying a new Internet architecture may, in fact, be possible.

Our contributions are as follows:

- We describe the value proposition for both end-users and ISPs showing that our approach benefits from natural scalability and wide-scale customer base reachability (Section 3).
- We design and implement DENA (Device for Enhancing Availability), a bump-in-the-wire device that can automatically detect and establish fail-over data paths over FIAs, and transparently fail-over to those paths when network quality is low. DENA requires no user configuration and is designed to be minimally
intrusive (Sections 3 and 5).

- We demonstrate, through a full-scale BGP simulation over the CAIDA Inferred AS Relationship dataset (45,942 ASes), that a small number (less than five) of ISPs deploying a FIA can significantly reduce attacks on availability (Section 7).

2. RELATED WORK

We review related work in two overarching themes: increasing network availability and incremental deployment of new architectures.

Several proposals aim to increase Internet availability. One avenue towards this objective is through the use of indirection. Andersen et al. [11] propose Resilient Overlay Network (RON) to shorten recovery time incurred from BGP outages by using an alternate network path through an overlay. While the work demonstrates the effectiveness of an overlay against BGP outages, it does not describe Internet-scale deployment issues where different ISPs can own different parts of the overlay. Our paper discusses deployment incentives for possibly competing ISPs.

Another closely related work is Advertised Reliable Routing Over Waypoints (ARROW). In their paper, Peter et al. [22] show that by redirecting traffic through tunnels, Internet reliability can be enhanced. The authors validate their claim through BGP simulations considering IP prefix hijacking attacks. The work herein corroborates the results of Peter et al. finding that redirecting traffic to a victim AS using a tunnel provides higher resilience against prefix hijacking attacks when an adversary targets the victim’s IP prefixes. Our simulation (see Section 6.4) encompasses a more comprehensive adversary strategy; unlike in ARROW, we analyze the case where adversaries are capable of attacking the tunnels as well as the victim AS. Additionally, our paper studies incremental deployment aspects of FIs, while the ARROW paper considers a minimal change that can provide the greatest increase in availability. For instance, the authors do not discuss how and who will manage the Internet Atlas, which is crucial for incremental deployment since such an atlas likely requires global coordination between the deploying ASes.

There have been proposals to study incremental deployability aspects of an architecture. In LISP (The Locator Identifier Separation Protocol), Saucez et al. [28] postulate “there must be a clear deployment path that benefits early adopters”. Ratnasamy et al. [24] distilled the properties that facilitate the deployment of a new architecture. They propose the use of IP anycast as the means to access the new architecture. We build upon the insights that Saucez et al. and Ratnasamy et al. have provided in terms incremental deployability. However, we avoid using IP anycast as the medium to access the new architecture because the use of anycast may preclude ISPs from engaging into a direct business relationship with customers. Instead, in our proposal an interested customer purchases a value-added service from a deploying ISP, and the ISP would distribute a gateway device to access its service.

3. BACKGROUND AND MOTIVATION

In this section, we motivate the need for network availability for ISPs and customers focusing on limitations of the Border Gateway Protocol (BGP).

3.1 Demand for Network Availability

The ever-increasing dependence on the Internet in our society has made availability a critical requirement for network infrastructure. We define availability to be the resilience against any type of attack or other network fault (e.g., misconfiguration) that could prevent or decrease the quality of a network connection.

Due to their core business model (i.e., offering connectivity to customers), ISPs require high network availability. We can infer the existence of this demand by analyzing the number of multi-homed endpoint ASes on the Internet. Using a snapshot of the CAIDA Inferred AS Relationships dataset [4], we observe that 22,386 out of 38,772 (approximately 57%) endpoint ASes have two or more provider ASes. Of these multi-homed ASes, 819 have five or more provider ASes. While there are reasons other than availability for ASes to be multi-homed (e.g., load-balancing, cost-balancing), multi-homed ASes are more likely to be accessible even if one of their BGP paths is unavailable.

Customers span the spectrum from residential end-users to large-scale enterprises to governments. A recent study found that residential users are becoming sensitive to quality of their home Internet connections [20]. Businesses, especially those which are geographically diverse, make use of Virtual Private Network (VPN) technologies to interconnect sites. For these businesses, the availability of intranet resources is tied to the availability of their Internet connectivity. Governments may want to ensure availability of their critical infrastructure to control smart grids or to ensure the success of online elections [20].

3.2 Degradation of Network Availability

Several factors may impact network availability on the Internet. These factors range from transient link failures to route changes to security vulnerabilities in routing protocols. Attacks on BGP are one of the major contributing factors to availability issues on the Internet today [3]. One of the most common threats in this context is known as IP Prefix Hijacking. Briefly, a BGP route is defined as an IP prefix and an AS-level path which leads to that prefix. Thus, IP prefix hijacking denotes the advertisement (malicious or accidental)
of a prefix which is not authorized for use by an advertising entity and which diverts the BGP path for that prefix to the hijacker. Due to the lack of authentication in BGP messages, IP prefix hijacking is relatively easy to perform as the adversary can announce any prefix of another AS (the standard threat model for this type of attack). As a consequence, false injection of update messages can be used to launch blackhole attacks which hijack and drop traffic to compromise availability. Although the following does not fundamentally protect BGP against hijacking attacks, we describe two practices that help in building a more secure path in BGP.

• **/24 Prefix Announcements:** Due to BGP’s default route selection policy, longer prefixes are harder to compromise than shorter prefixes. However, ISPs are hesitant to accept /24 prefix announcements persuasively because doing so would dramatically increase the size of routing tables on their border routers.

• **Shorter BGP Paths:** Shorter paths are usually more resilient than longer paths because border routers typically prefer routes with shorter AS-Path length. As the number of AS hops decreases, there are fewer network locations (routers) from which an attack could be launched. Thus, if a route between two end-hosts could be divided into multiple shorter path segments, it would be more secure than the single longer path between the two end-hosts. We confirm this effect through BGP simulation in Section 7.

### 3.3 Value Proposition for Early Adopters

**Value for ISPs.** As early adopters, ISPs that deploy an FIA obtain several benefits. First, deploying ISPs’ benefit from higher availability by increasing their resilience to hijacking attacks (see Figure 8); and, the benefit exist even with a small number (see Figure 9) of deploying ASes.

The benefit is accrued without sacrificing the scalability of BGP routing tables. If every domain were to announce /24 prefixes for higher availability (i.e., stronger resilience against IP prefix hijacking attacks), the BGP routing table does not scale. Instead, in our approach, since only a few initially deploying ASes announce /24 prefixes to protect their tunnels, the overhead on BGP routing tables is small. Furthermore, beyond initial deployment, our approach benefits from natural scalability: as more ISPs deploy the FIA, fewer /24 announcements are needed since two contiguous ISPs that deploy FIA can communicate directly without a /24 announcement. Consequently, we expect the number of announced /24 tunnel prefixes to increase during the early stage of deployment and decrease as more ISPs deploy.

Second, there may exist a business incentive for deploying ISPs to offer high availability to customers of other ISPs (e.g., via IP tunnels as described in Section 4.1). Lastly, ISPs can create a niche market for a set of customers who demand higher availability than BGP can provide but cannot afford dedicated leased lines.

**Value for Customers.** Customers may obtain high-availability (even if the customer’s local ISP does not provide such functionality) by subscribing to a remote provider via an access tunnel. More importantly, customers can be bridged into high-availability architectures without changes to software on their local devices or modifications to their Internet service. We show one method to achieve this zero-configuration setup in Section 4.

### 4. OVERVIEW AND REQUIREMENTS FOR A HIGH-AVAILABILITY DEVICE

Guaranteeing benefits under partial deployment alone is not sufficient for a successful initial deployment. Customers must be able to subscribe to an FIA without carrying out any complicated tasks, such as configuring their network devices or updating them to a new network stack—updating the network stack on light bulbs, cameras, televisions, refrigerators, and other Internet of things devices may be infeasible. To this end, we develop a **bump-in-the-wire** interface device which we refer to as DENA (Device for ENhancing Availability) to be placed between the customer’s network and their Internet provider. An alternative approach could be to deploy such interface devices at the ISPs themselves (this approach is used by Peter et al. [22]), completely removing end-user involvement. However, this strategy would preclude users from subscribing to the FIA if their immediate ISP does not deploy it.

The primary function of DENA is to increase Internet availability to its subscriber by leveraging a given FIA as a fail-over network. That is, if the IP path between two customers (deploying end-points) becomes unavailable, DENA would detect the unavailability and automatically fail-over to a path through the FIA by encapsulating IP packets.

To provide high-availability guarantees, DENA devices need to implement four functionalities. For a given communication flow between a subscriber and a peer, the DENA needs to 1) identify the presence of a peer; 2) if present, establish FIA path(s) to be used as fail-over; 3) continuously measure the packet loss rate of the path(s); and 4) fail-over to a path offered by the FIA if necessary.

Although our design and implementation of DENA remains generic for any FIA that is capable of providing high-availability guarantees (e.g., NIRA and SCION), throughout the following sections, we draw on SCION as the chosen example FIA. We find it useful to focus on one particular FIA to keep the discussion concrete and to drive the narrative. In addition, our access to the global SCION testbed enables for a thorough evaluation of our implementation.

For space reasons, we do not provide details of the SCION architecture in this paper; however, the discussions in the following sections should be clear without any prior knowledge of SCION (Zhang et al. [34]).

#### 4.1 ISP Deployment Model

To minimize impact on their current infrastructure, ISPs
are likely to deploy a high-availability infrastructure as an overlay to their current networks. Customers, as well as other ISPs will use IP tunnels to bridge into these overlays.

Hence, constructing reliable tunnels is essential to provide high-availability guarantees. To this end, /24 prefix blocks are used to reduce the risk of traffic hijacking attacks against the tunnels.

For our deployment strategy, we define the following tunnel types (shown in Figure 1), and explain how tunnels are protected against hijacking by using the practices described in Section 3.2.

**Access Tunnel.** A tunnel with which a deploying ISP can offer high-availability services to customers whose ISPs do not support these features. As shown in Figure 1a, to protect the tunnel between A and itself from hijacking, the deploying AS (D1) announces a /24 prefix that contains the IP address used for that tunnel. This announcement reduces the probability of an adversary successfully hijacking this tunnel if they are multiple hops away from A and D1.

**Inter-site Tunnel.** A tunnel that connects two non-contiguous deploying ASes over the Internet (see Figure 1). The ASes need to protect the tunnels that link deploying sites from prefix hijacking attacks. Similar to the access tunnels above, each of the two ASes announces a /24 prefix block that contains the IP address used as its tunnel end-point address.

**End-to-end Tunnel.** A series of tunnels that consist of access tunnels and inter-site tunnels to connect customers A and B over the FIA deployment. For instance, in Figure 1, the end-to-end tunnel consists of one access tunnel and one inter-site tunnel.

### 4.2 End-to-End Communication Scenario

Before describing the design and implementation of DENA, we sketch a high-level picture of how an end-to-end communication flow would behave in a typical Internet-wide scenario shown in Figure 2.

In this scenario, there are two SCION providers (Prov1, Prov2) that have deployed gateways (GW1, GW2) to serve their SCION subscribers. There are three end-hosts (Host1, Host2, Host3), where Host1 has a public IP address, and Host2 and Host3 are behind a NAT. To enhance their Internet availability, Host1 has subscribed to the SCION service from Prov1, and Host2 and Host3 from Prov2. All hosts have placed DENA devices as bump-in-the-wire on their network connection.

Consider a scenario where Host2 initiates communication to Host1. Upon receiving a packet from Host2, DENA2 checks if it knows the peer DENA associated with the destination address of the packets. If it does not know the associated peer, DENA2 initiates a Discovery Process (Section 5.1) and exchanges bootstrapping information that is necessary for constructing SCION overlay paths to the remote peer. In addition, the bootstrapping information contains information necessary for NAT traversal, which we discuss in Section 8.

A DENA monitors the packet loss rates of the paths (both IP and SCION paths) to all of the discovered peer DENAs (Section 5.2). Whenever the quality of the IP path to a peer DENA degrades below a given threshold, and the quality of a path provided by SCION is acceptable, all of the flows associated with the peer DENA are encapsulated and redirected to the SCION path to ensure continued availability.

Redirection over SCION is accomplished via a series of tunnels using the packet structure shown in Figure 3. The first and last tunnels are access tunnels (see Figure 1a) between the DENAs and the SCION gateways. The intermediate tunnel is a series of inter-site tunnels (see Figure 1b) that links the two SCION ASes to which the two end-hosts are subscribed.

In our communication example between Host2 and Host1, the packets from Host2 to Host1 traverse from DENA2 to DENA1 via tunnels across DENA2 to GW2, Prov2 to Prov1, and GW1 to DENA1. DENA1 removes the tunnel header and the SCION header, and forwards the regular IP packets to Host1.

| IP Tunnel Header | SCION Header | Data Header | Data Payload |
|------------------|--------------|-------------|-------------|

**Figure 3: Packet structure over SCION**

### 4.3 Requirements

Previous work in the incremental deployment literature [9][4][28] has discussed desirable properties for an architecture to gain adopters. These properties mainly refer to the need for incentivized adoption, independence from ISPs that hosts buy their Internet connection from, and compatibility with existing devices and infrastructure. Based on these properties, we define the design requirements for our own incremental deployment device.

**Req 1. No Changes to End-hosts:** End-hosts should not require any modification to make use of the FIA. Rather, DENA should operate as an interface between the current
Internet and FIA, enabling a smooth transition between the two architectures.

**Req 2. Zero configuration:** DENA should operate as a “plug-and-play” device and should not require any configuration by users. However, similarly to wireless access points, a DENA should allow fine-tuning of parameters by advanced users.

**Req 3. Robustness:** DENA should work under a majority of network configuration scenarios and in the presence of packet-modifying or packet-filtering middleboxes (e.g., NATs and firewalls).

**Req 4. Autonomous peer discovery:** DENA should not require any additional infrastructure to detect a peer DENA. Such additional requirements would create complications regarding who would build and maintain the additional infrastructure and these complications will hinder incremental deployment.

## 5. DESIGN AND IMPLEMENTATION OF DENA

This section describes the DENA design shown in Figure 4, which shows the major components (discovery protocol and path management) and the corresponding sections where the descriptions for the components can be found.

![Diagram](image-url)  
**Figure 4:** Major DENA components.

### 5.1 Discovery Protocol

The goals of the DENA discovery protocol are 1) to automatically and transparently (i.e., without interfering with active data flows) detect the presence of a remote peer and 2) to exchange bootstrapping information that is necessary for constructing paths over SCION to the peer DENA.

Discovery is performed whenever a DENA device detects a new communication flow, identified by the 5-tuple information (source IP, destination IP, source port, destination port, and protocol number) of the packets in the flow. Ports are used in addition to the source and destination address pairs so that DENAs behind a shared NAT can be distinguished and identified. For example, in Figure 4, DENA1 cannot identify whether the communication flow is being forwarded by DENA2 or DENA3 based only on the IP address because the packets forwarded by both DENAs would have the same source IP address, 5.5.5.5.

Before describing the two parts of the discovery procedure (detection and bootstrapping), we describe the signaling channel that is fundamental to our discovery procedure.

#### 5.1.1 Signaling Channel

The most important challenge in DENA detection is to construct a reliable signaling channel to the peer DENA through which the DENA discovery message is transmitted. Naively, one can define a dedicated UDP or TCP port, and send a discovery message to that port. Although the approach may work for general cases, it can be problematic in the presence of middle-boxes such as firewalls and intrusion detection systems. Additionally, users may be required to perform manual configurations on such devices, which violates the zero-configuration requirement from Section 4.3.

Alternatively, we suggest constructing the signaling channel using end-hosts’ traffic. This type of channel has been widely studied in network steganography with two generic approaches [16]: 1) manipulating structure of packet streams (i.e., temporal variation in packet transmission times); and 2) manipulating packet headers, such as IP and TCP headers. Although the signaling channel constructed via the former method tend to be more robust against various middle-boxes, it unavoidably introduces undesirable delay and jitter into end-hosts’ communication [17]. Thus, we use the latter method to construct the signaling channel.
To make DENA compatible with any IP based protocols, we use the TTL and Identification (IPID) fields in the IP header. Note that while we are hiding signals inside the IP header, this is done for compatibility rather than for security. That is, our objective is not to prevent an observer from seeing that the channel is being established, but rather to prevent the signaling messages from being parsed (possibly incorrectly) by the destination device in case a DENA device is absent.

**TTL.** Although 255 is the literal maximum value of the TTL field, IP paths on the Internet are generally shorter than 64 router hops (with 64 being the recommended initial TTL value [27]). Hence, it is possible to decode the values that the sender has chosen if the initial TTL values are chosen to be at least 64 units apart. Since there can only be tuples of at most three TTL values that are 64 units apart from each other, we define three signals A, B, C from three TTL values, 64, 128, 192, respectively.

**IPID.** Since the use of the IPID field remains unspecified for unfragmented packets, the field can be used to embed hidden signals [31]. We define three hidden signals from the IPID values so that the DENA detection procedure can be used with both TTL-based and IPID-based signals.

We choose three sets of IPID values whose 12 most significant bits (MSBs) are 0x001, 0x7FF, 0xFFF as signals A, B, and C, respectively. The values are chosen to be maximally spaced apart (without including IPID value of zero) to prevent operating systems that increment the IPID value by one for each transmitted packet, from accidentally transmitting all three of our defined signals during the DENA detection procedure. In addition, there are 16 IPID values that correspond to a hidden signal. Although fragmentation is discouraged in practice (for efficiency reasons), fragmented packets do exist on the Internet [30]. The last four bits can change to repeat our signals even when some of the IPID values are used for fragmented packets.

### 5.1.2 DENA Detection

For detection, every DENA device periodically announces the discovery messages and responds to the received discovery messages with the bootstrapping information (defined in Section 5.1.3).

The discovery message is defined as a sequence of signals known to all DENAs a priori (See Table 1 in Section 5). Because the message is a sequence of hidden signals, the message is encoded into a stream of consecutive packets. Hence, when announcing the discovery message, a DENA modifies the TTL and the IP ID fields of the packets that it is forwarding. In our design, both TTL and IPID fields are used to encode the same hidden signals to enhance the robustness of DENA detection. Thus, even when one of the fields gets scrubbed by middle-boxes, DENAs can use the other signal to decode the discovery message.

In addition to periodically emitting the discovery message, DENA listens for the discovery message by examining the TTL and IPID fields from streams of incoming packets. Identifying the discovery message from a stream of packets is a challenge because the Internet, as a communication channel, may reorder, lose or duplicate packets. In fact, the decoding problem at hand is similar to the well-known insertion-deletion channel problem to which an efficient decoding algorithm is not yet found [18].

Combinatorial methods, which compute the difference between the transmitted and received messages, have been studied for decoding under insertion-deletion channel. Edit distance (i.e., Levenshtein distance [14]) provides a metric to compare the difference between the two messages based on the minimal number of edits (insertion, deletion, replacement) that are necessary to transform one message to the other. In our design, DENA concludes the presence of a peer if the edit distance between the discovery message and the received message is below the detection threshold value (i.e., fewer number of edits than the detection threshold).

A DENA may falsely conclude the presence of a peer DENA. On one hand, a DENA may fail to detect a remote peer that is present (i.e., false negative) because the Internet may drop or reorder the discovery message that the DENA sends to its peer. On the other hand, a DENA may falsely detect a peer that is not present (i.e., false positive) due to the IPID fields in a stream of packets accidentally having the right sequence as the discovery message. There are trade-offs between these two probabilities, and they depend on the decoding parameters, such as the length of the discovery message as well as the detection threshold value.

When the decoding is solely based on edit distance, the false positive probability can be high. To lower the false positives, we place a light-weight pre-filter that checks the approximate structure of the received message before computing the edit distance. The pre-filter lowers the false positive probability while increasing the probabilities of the false negatives. For an example design of the pre-filter and the detection error analysis, see Section 6.

### 5.1.3 DENA Bootstrapping

After detecting the presence of a peer, bootstrapping information that is necessary for constructing SCION paths is transmitted. The information can be transmitted through the signaling channel described in Section 5.1.1. However, since the signaling channel has very small capacity (i.e., \( \log_2(3) \) bits per packet), the channel’s capacity is too small to send the bootstrapping information. (i.e., 10 bytes are needed for SCION).

Alternatively, we define an out-of-band control-packet that is generated by the DENAs to communicate bootstrapping information. Since a DENA has detected the presence of a peer, it can send a dedicated packet knowing that it will

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1. During our experiment, we encountered a middle-box that scrubs the TTL fields but keeps the IPID fields intact for TCP flows.

2. Assuming perfect channel that does not lose, re-order, or duplicate packets.
be parsed and discarded by the peer DENA before the packet reaches the peer end-host. Hence, the control packets do not disrupt end-host communication.

The control packet must be carefully constructed so that it can be reliably delivered to the intended DENA, passing through middle-boxes that may be present. To this end, control packets are created by duplicating the end-hosts’ packets. For UDP packets, the fact that end-hosts’ packets can reach the destination ensures that the control packet would be able to reach the peer DENA. For TCP packets, middle-boxes have no choice but to accept the control packets, as it cannot tell whether the control packets are generated due to routine packet re-transmissions in the TCP protocol.

After duplicating end-host’s packet, the payload (after the IP and transport header) is modified as follows. A DENA identifier message is added at the beginning to indicate that the message is a DENA control packet. Then the message type to indicate the type of the control message and the message payload are added.

5.2 Path Management

To achieve a high level of availability, it is necessary to periodically monitor the status and quality of both the IP path and the SCION paths. Whenever the quality of the IP path degrades below a threshold, communication between end-hosts is switched over to a higher-quality path offered by SCION. Furthermore, even after the switch, the IP path is constantly monitored so that the communication may switch back to the IP path after it is again reliable.

5.2.1 Path Quality Measurement

A DENA periodically measures packet loss rates for both IP and SCION paths to all peer DENAs found during the DENA Discovery Procedure. Unlike the DENA Discovery Procedure, which is performed per flow, path measurement is done per peer DENA. An advantage of this approach is that it enables more accurate measurement, since a DENA can have many associated flows (e.g., multiple concurrent TCP connections to an HTTP server).

Measurement of the Active Path. For path quality measurement of the active path, we rely on data packets from end-hosts that are flowing between a pair of DENAs. We adopt a packet loss measurement method that has been used for quality measurements in MPLS networks [6]. Briefly, the proposal uses a pair of measuring points each of which maintains two counters for counting incoming and outgoing packets, and computes packet loss rates based on the four counters.

Specifically, the measurement proceeds as follows between two measuring points, A and B. First, A initiates the measurement by sending a request message to B with the outgoing packet counter value at the moment that the request is made. Then B replies to the request with the value of the incoming packet counter as well as its outgoing packet counter value. Upon receiving the reply, A marks its value of the incoming packet counter. Finally, using the four counter values, A computes the packet loss rate, which is defined to be the maximum of the loss rates between incoming and outgoing paths.

When computing the packet loss rate, the difference in counter values from current and past measurements are used. Thus, the two measurement points A and B do not need to synchronize the starting time at which both points start counting outgoing and incoming packets.

For our context, the two measurement points would be the pair of DENAs. In addition, the measurement request and reply packets needed for the measurement are implemented using the DENA control messages described in Section 5.1.2.

The MPLS measurement approach offers several advantages for our implementation. First, it is light-weight; second, synchronization between two DENAs is not necessary; third, two-way channel delay can be computed with only a small additional overhead (see Frost et al. [6] for details).

Measurement for Fail-over Paths. The quality of the fail-over paths must be monitored so that the DENA can ensure that the fail-over paths are healthy when attempting to send data traffic over one of these paths. However, the passive MPLS measurement cannot be used directly for the fail-over path since no data traverse them.

To overcome such problem, we sample the traffic flowing though the active path and transmit this traffic over the fail-over paths. Since the loss rate of both outgoing and incoming traffic are necessary, we need bi-directional traffic flowing through the fail-over paths. Hence, the two DENAs need to coordinate the time when data traffic through the active path is replicated on the fail-over paths.

To coordinate the measurement intervals between two DENAs, we use the DENA control channel (Section 5.1.3). Two DENAs exchange a “start message” to start the measurement and a “stop message” to stop the measurement. An advantage of this approach is that it requires no form of time synchronization, which can be difficult to achieve without introducing additional complexity.

Figure 5: State machine for the Path Quality Measurement.

Figure 5 shows the state machine for the path quality meas-
measurement, which consists of three phases. The Initiation Phase is started when DENA transmits the Start message and is completed when the initiating device receives a Start ACK message from a peer. The initiating and responding DENAs are decided based on the ID values that they exchange during the bootstrapping phase.

During the Measurement Phase, each DENA performs the measurement to compute the packet loss rates of the fail-over paths. Once the measurement is complete, the two peers listen for Stop messages that are used for terminating the measurement. In addition, both DENAs maintain timers to mark the end of the measurement period. A DENA sends a Stop message to its peer when the timer expires. Upon successfully exchanging the Stop and Stop ACK messages between the two DENAs, the path measurement cycle is completed.

In addition to marking the end of an measurement interval, the Stop and Stop ACK messages serve another purpose. These messages contain the packet loss rates and their decisions regarding which path to use to forward end-hosts’ data traffic.

Lastly, similar to the TCP connection tear-down procedure, we implement a timeout state (i.e., Time_Wait state) so that a DENA that sends the Stop ACK is sure that the peer DENA has received the Stop ACK message.

Path Keep-Alive based on Active Probing In cases where a path drops all packets (e.g., link failure), our measurement does not work. To cope with such failures, a DENA periodically exchanges ICMP probe messages with the peer DENA through all available paths. If a DENA does not receive any response for consecutive probe messages from a path, the DENA considers the path to be unavailable. Additionally, the DENA immediately terminates the ongoing path measurement and starts a new measurement.

5.2.2 Path Selection

Path selection is performed whenever a path measurement is completed (when DENA reaches the Done state). A new path is selected as follows: 1) whenever the loss rate of the IP path is lower than the threshold, a DENA chooses the IP path, 2) if the loss rate is higher than the threshold and if there is a SCION path that has lower packet loss rate than the threshold the SCION path is chosen, 3) if none of the paths has lower packet loss rate than the threshold, the path with the lowest loss rate is chosen.

5.3 Implementation

The proof-of-concept prototype of the DENA consists of 3K lines of C code. The implementation runs on Linux, using the Netfilter Queue (nfqueue) Library which enables IP tables firewall decisions to be made in user-space. We use the nfqueue library, which allows packet modification before accepting a packet, to manipulate packets and encode the hidden signals. DENA control messages also make use of the library.

6. EVALUATION OF DENA DESIGN

We validate our design and implementation of DENA through simulation and real-world evaluation over the SCION testbed. More specifically, we are interested in 1) ensuring our implementation meets design objectives; 2) confirming that the FIA measuring the false positive and false negative probabilities during DENA detection; and 3) evaluating the effectiveness of the path quality measurement described in Section 5.2.1.

6.1 Conformance to Requirements

DENAs are deployed between the customer’s end-hosts and their Internet connection, which requires no changes to the end-host itself (Req 1). DENAs do not require any manual configuration (such as IP addresses) by users. Once configured by ISPs, DENAs are designed to be plug-and-play (Req 2).

Although DENAs generate control packets, these packets by design are not forwarded to end-hosts. Thus, end-hosts should never receive or need to parse control packets. DENAs can work in the presence of various types of middle-boxes and NATs, which satisfies the robustness requirement (Req 3). Furthermore, as control packets (which are opportunistically duplicated from end-host traffic) are indistinguishable from data packets at the IP and transport layers, they can be forwarded by middle-boxes without being filtered.

Finally, the DENA Discovery Procedure satisfies the self-discovery requirement (Req 4), since it does not require additional infrastructure for peer DENA detection.

6.2 DENA Detection Procedure Analysis

As discussed in Section 5.1.2, the proposed DENA detection procedure is subject to both false positives (i.e., detecting a DENA when it is not present) and false negatives (i.e., not detecting a DENA when it is present). In this section we evaluate false positive and false negative probabilities through simulation. We summarize the parameters that we use for the DENA simulation and implementation in Table 1.

Figure 6 shows the probability that a DENA fails to detect the presence of a peer as packet loss rates are varied at 1% increments from 0% to 10% within five attempts of DENA detection. For precision, we take the average of one million runs for each fixed packet loss rate. As expected, the false negative probability increases with increased packet loss rate. In addition, the false negative probability is higher when the pre-filter is not used or when the lower edit distance threshold value is used.

Furthermore, false negative probability decreases exponentially as the DENA Detection is performed multiple times (not shown in Figure). For example, at 10% packet loss rate, there is about 35% chance that a DENA fails.
to detect a remote peer if the detection procedure is performed only once for the case with pre-filter and the detection threshold of three. However, when the detection procedure is repeated for five times, the false negative probability decreases to about 0.6% as shown in Figure 6.

![Figure 6: Probability that DENA fails to detect it a remote peer within five attempts of the detection procedure.](image)

A trade-off exists between missed detection and incorrect detection. That is, the settings that have yielded higher false negative probability have lower false positive detection probability. To simulate this effect, we input a stream of packets that consists of one million packets where a random IPID value is chosen for each of the one million packets. Then, we check whether a DENA would incorrectly identify the presence of a peer within the stream. We repeat this simulation 10,000 times to get an estimate of the false positive probability, and the results are summarized in Table 2.

![Table 1: Parameter settings for the DENA simulation and implementation.](image)

| Discovery Message | ABABABABCCCCCCABABABAB |
|-------------------|--------------------------|
| Pre-Filter        | 1. Divide decoded message into 3 blocks of 8 signals.  
|                   | 2. Check if there are at least three A-signals and three B-signals each in the first and the third blocks  
|                   | 3. Check if there are at least six C-signals in the second block |
| Edit distance     | 3 or 5 |
| Threshold         | 1 seconds |
| Meas. Interval    | 1 seconds |
| Meas. Period      | 1 seconds |
| Path Switch       | 5% Packet Loss |

Table 2: False positive probability of the DENA Detection Procedure against a stream of one million packets with random IPID values.

| Threshold | w/ prefilter | w/o prefilter |
|-----------|--------------|---------------|
| 5         | 0.02%        | 0.03%         |
| 5         | 4.4%         | 11.8%         |

6.3 Path Switching Based on Path Quality Measurement

The purpose of this experiment is to confirm that our DENA implementation can react to the change in path quality and switch the end-hosts’ traffic to alternate paths if necessary. For the experiment setup, we deployed two DENAs on the SCION global testbed. One was placed at ETH Zürich (AS6) and the other at CMU (AS14). We placed a WANem Emulator [29] on the IP path from AS6 to AS14, which allowed us to introduce arbitrary packet loss rates into the IP path.

We deploy an end-host that runs an HTTP server in AS14, and deploy an end-host that downloads (via the wget application) a large file from the HTTP server in AS6. At approximately 80 seconds into the file download, we introduce 10% packet loss on the IP path, and then remove the packet loss at around 110 seconds.

At the end-host in AS6, we record the throughput of the file download as well as the data rates on both paths to validate our implementation. Throughput information is plotted in Figure 7 showing the change in throughput over time as for the wget application as well as the two paths.

Initially, the end-host’s traffic flows through the IP path. In addition, there is about 10% of the traffic flowing through the SCION path for measuring the path loss rate of the failover path. When 10% packet loss is introduced on the IP path at around 81 seconds, the two DENAs switch over to the SCION path about 2 seconds into the degradation. The switch can be verified by the increase in throughput at the SCION path to that of the actual file-transfer rate as well as the decrease in throughput at the IP path.

Finally, after the 10% packet loss is removed from the IP path, the DENAs move the end-hosts’ traffic back to the IP path after about two seconds of delay. This test was repeated 5 times obtaining comparable results in each iteration.

7. DEPLOYMENT ANALYSIS

In the previous section, we have shown that DENA can improve the availability of the end-hosts’ connections despite changes in network conditions (e.g., when there is a packet loss in the Internet). In this section, we evaluate the availability benefits of a FIA when there are adversaries that perform IP prefix hijacking attacks. In addition, we analyze the benefits that deploying ISPs could accrue.

To evaluate the deployability and availability benefits of a FIA, we perform series of BGP simulations by extending the BSIM simulator [13], where the BGP paths are computed us-
ing route selection based on the standard BGP routing policies (Gao-Rexford Model [7]). As our topology dataset, we use a recent snapshot of the CAIDA Inferred AS Relationship dataset.

### 7.1 Tunneled Paths Resilience

The announcement of /24 prefixes for the tunnels offers protection of the tunnels against prefix hijacking attacks; however, the /24 prefix announcements cannot prevent all hijacking attacks. As the length (in AS hops) of the tunnel increases, the resiliency against hijacking decreases. In this section, we investigate the benefit (i.e., resilience against prefix hijacking attack) that a path constructed using a series of short tunnels can provide over a single BGP path.

For our study, we use the following notation:

- \((AS_x, AS_y)\): BGP path (list of ASes) between \(AS_x\) and \(AS_y\).
- \(|(AS_x, AS_y)|\): length (expressed in AS-level links) of \((AS_x, AS_y)\) path.
- \(T_N\): number of deploying ASes \(AS_1, AS_2, ..., AS_{TN}\) that form the overlay end-to-end tunnel.
- \(T_L\): length of the longest tunnel segment (i.e., maximum \(|(AS_i, AS_{i+1})|\) for \(i \in [1, T_N - 1]\)).
- \(L_{BGP}\): length of the BGP path between \(AS_1\) and \(AS_{TN}\) (i.e., \(|(AS_1, AS_{TN})|\)).
- \(L_T\): length of the tunneled path between \(AS_1\) and \(AS_{TN}\) (i.e., \(\sum_{i=1}^{T_N-1} |(AS_i, AS_{i+1})|\)).

We assume that the first node of an end-to-end tunnel path (\(AS_1\)) is the source while the last (\(AS_{TN}\)) is the destination. Then, \(L_{BGP}\) expresses the length of the BGP path between source and destination. We also assume that traffic from source to destination over the end-to-end tunnel traverses overlay nodes \(AS_2, AS_3, ..., AS_{TN-1}\) in that order. The tunnel’s path on an AS-level is a concatenation of BGP paths: \((AS_1, AS_2), (AS_2, AS_3), ..., (AS_{TN-1}, AS_{TN})\).

For our simulation, we consider two adversary strategies designed to hijack traffic from source to destination: 1) weak adversary which announces only the destination’s prefix, and 2) strong adversary which announces all prefixes of \(AS_2, AS_3, ..., AS_{TN}\). In both cases an adversary launches attacks from a randomly compromised AS, however he cannot compromise ASes on the path between source and destination. Note that ARROW [22] only considers the weak adversary model and does not consider the strong adversary model.

In this experiment, we simulate 8 scenarios by varying \(T_N, T_L, L_{BGP}\) to analyze the resilience that tunnels can provide against prefix hijacking attacks. For each scenario, while incrementing the number of adversarial ASes from 1 to 7, we construct and simulate 1000 random and unique tunnel deployments, where \(T_1\) and \(T_N\) are randomly chosen from multi-homed stub ASes and the other tunnel nodes are chosen from all other ASes.

Figure 8 summarizes the results of our simulation. In each graph in the figure, the x-axis represents the number of adversaries (varied from 1 to 7) and the y-axis represents probability values that an attack on the tunneled path will be successful. The two figures on the left show the hijack probability of the tunneled path for source and destination AS pairs that are four BGP hops apart \((L_{BGP}=4)\); and, on the right five BGP hops apart \((L_{BGP}=5)\). Moreover, the upper two figures show the results against weak adversaries while the lower two figures show the results against strong adversaries. Lastly, each plot also shows hijack probability for the BGP paths (green line with plus markers).

Our results show that the hijack probability increases as the number of adversaries increases and that the probability is higher for the strong adversary model than the weak adversary model. Furthermore, against the weak adversary model, the probabilities of hijacking the tunneled paths are similar for the two cases that have the same tunnel segment length (i.e., \(T_L\)) but different total length (i.e., \(L_T\))—on the upper two figures, the purple lines with diamond markers and the red line with inverted triangle markers almost overlap with each other. This is because the weak adversary model can only attack the last tunnel segment (i.e., \((T_{N-1}, T_N)\)) as the weak adversaries only announce the prefix of the destination (i.e., \(T_N\)).

The results show that the tunneled paths have lower hijack probability than the BGP paths even if the length of the tunneled path (i.e., \(L_T\)) is longer than that of the BGP paths (i.e., \(L_{BGP}\)). But, the result also shows that if the length of the tunneled paths becomes too long (e.g., twice the length of the BGP paths), the tunneled paths become more susceptible to hijacking attacks. However, in practice, it is highly unlikely that the tunneled paths would be twice the length of the BGP paths.

Lastly, the results show that the composition of the tunneled path affects the resilience against prefix hijacking attacks: a tunneled path that is composed of shorter individual segments is more resilient than a path that is composed of longer individual segments. For the two cases where

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To build more confidence of our results, we have run four independent sets of 1000 deployments for all 8 scenarios and confirmed that the results were similar across the four sets.
Let $T^L \leq 6$, the hijack probability is significantly lower when the length of the individual tunnel is kept shorter. In Figure 8, this can be seen by comparing the blue line with 'x' markers and the purple line with diamond markers. Moreover, the result shows that the tunneled paths that have longer total length but shorter individual tunnel segments (i.e., $T^L \leq 8$, red lines with inverted triangle markers) is more resilient than the tunneled paths that have shorter total length but longer individual segments (i.e., $T^L \leq 6$, blue lines with 'x' markers).

### 7.2 Potential Customer Base

In this section, we investigate the proportion of multi-homed stub ASes that are $N$-hops (i.e., $T^L = N$) away from any of the deploying ASes as we vary the number of ASes which deploy the FIA. This experiment should assist in quantifying the potential customer base (measured in number of ASes) as the FIA deployment increases.

Figure 9: Proportion of ASes that can communicate over FIA.

In this experiment, we randomly choose ASes to deploy the FIA such that the distance between deploying ASes would be at most $N$ BGP hops (i.e., $T^L = N$). Then, for all multi-homed stub ASes, we evaluate the number of ASes that are within $N$ hops from any of the FIA deploying ASes.

Figure 9 shows the proportion of the ASes that could be reached within $N$ hops from the FIA deployment as number of deploying AS changes from 1 to 20.

Our results show that for higher values of $T^L$, a larger portion of the multi-homed stub ASes were within the reach of the deploying ASes. Combining the results from Section 7.1, we can conclude that for large values of $T^L$, deploying ASes obtain larger customer-base at the expense of availability guarantees against prefix hijacking attacks. Conversely, when offering higher availability guarantees, the customer-base becomes much smaller (i.e., $T^L = 2$).

As expected, the number of deploying ASes increases with the size of customer base. In fact, when there are 20 deploying ASes, the customer-base nearly spans across the entire Internet for the cases with $T^L \geq 4$. In addition, even with only one deploying AS, there are multi-homed stub ASes that could benefit from the FIA deployment, and for the cases with $T^L \geq 4$, more than half of the multi-homed stub ASes could access the FIA deployment within $T^L$ hops.

Lastly, Figure 9 offers another interesting observation—reduced benefit (in terms of increase in customer base) as more ASes participate in FIA deployment. This can be inferred from the gradient of the plots, which tends to zero as $N$ increases. Hence, the result suggests that beyond the initial phase of the deployment, a different incentive model may be necessary to further drive the FIA deployment.

### 8. DISCUSSION

#### 8.1 Practical Implications on Deployment
NAT Implications. As discussed in Section 4.3, a DENA should work in the presence of middle-boxes such as NATs. When a DENA is placed in-between a NAT and an end-host (see DENA2 in Figure 2), communication over the SCION path may not work. For instance, when the communication between Host1 and Host2 in Figure 2 is carried out through the SCION path, DENA2 cannot deliver Host1’s packets to Host2 without being given Host2’s internal address.

To address this problem, when DENA2 and DENA1 exchange bootstrapping information during the DENA Discovery Process, DENA2 includes the private address of Host2.

Another problem is the communication between GW2 and DENA2. Because of NAT, GW2 cannot send a packet to DENA2 before DENA2 starts forwarding packets via SCION. To avoid this problem, DENA2 periodically exchanges keep-alive messages to its assigned gateway, performing NAT hole-punching. Since the DENA itself does not have an IP address, it borrows one of the IP addresses it has learned from the end-hosts to perform the hole-punching.

MTU Implications. The measurement and correct configuration of MTU size is critical for any scheme that requires encapsulation, such as the tunnels used in our system. When end-hosts perform the path MTU discovery protocol (PMTUD [19]), DENA can respond with an MTU size small enough to provide enough space for encapsulation. In the event that an end-host does not respond to PMTUD messages (fewer than 10% of devices do not [15]), packet fragmentation would be required, increasing the complexity.

8.2 Device Configuration and Distribution

Although DENA does not require any configuration by end-users, it requires configuration by ISPs prior to distribution to customers. Configuration would include information necessary for bootstrapping the DENA into the FIA deployment (i.e., in case of SCION, this includes SCION ISD ID, AS AID2 and IP address of the gateway that a DENA would contact to access the SCION network). We note that such configurations are common in today’s Internet when ISPs distribute cable or DSL modems to their subscribers. In addition, for customers that already have access devices (i.e., cable or DSL modems), the firmwares of these devices could be updated to support DENA functionality.

8.3 Applicability to Other FIAs

The DENA is a generic device that creates tunnels to interconnect two FIA deploying islands. Hence, it is possible to use DENA for other FIAs, as long as tunneling can be used to interconnect two FIA deploying islands. The important part in bootstrapping a FIA is to identify the proper incentives for the early adopters. For instance, for more efficient distribution and access to the content to early adopters,

NDN could be deployed. In NDN deployment, DENA would translate user data requests into an interest packet and send it to the NDN deployment. When the requested data arrives at the DENA, it delivers the data to the user.

9. CONCLUSION

We have motivated, designed, and evaluated an incremental deployment strategy for Future Internet Architectures. Through both simulation and real-world implementation and testing, we demonstrated tangible availability improvements for deploying ISPs with comparatively little deployment cost. Our evaluation used SCION to assess the feasibility of our proposal, but the proposed incremental deployment strategy remains compatible with other FIAs.

While availability alone will likely be insufficient to motivate full wide-scale deployment, this paper focuses on convincing early adopters to use a new architecture. Once a base set of ISPs and customers have deployed a FIA, a new strategy may be necessary to encourage a majority of ISPs to deploy. For example, the next set of deploying users could be interested in mobility or content-centric networking, but such analysis is left open to future research.

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