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Current Open Questions in Path-Aware Networking

Abstract

In contrast to the present Internet architecture, a path-aware internetworking architecture has two important properties: it exposes the properties of available Internet paths to endpoints, and it provides for endpoints and applications to use these properties to select paths through the Internet for their traffic. While this property of "path awareness" already exists in many Internet-connected networks within single domains and via administrative interfaces to the network layer, a fully path-aware internetwork expands these concepts across layers and across the Internet.

This document poses questions in path-aware networking, open as of 2021, that must be answered in the design, development, and deployment of path-aware internetworks. It was originally written to frame discussions in the Path Aware Networking Research Group (PANRG), and has been published to snapshot current thinking in this space.

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1. Introduction to Path-Aware Networking

In the current Internet architecture, the network layer provides a best-effort service to the endpoints using it, without verifiability of the properties of the path between the endpoints. While there are network-layer technologies that attempt better-than-best-effort delivery, the interfaces to these are generally administrative as opposed to endpoint exposed (e.g., Path Computation Element (PCE) [RFC4655] and Software-Defined Wide Area Network (SD-WAN) approaches), and they are often restricted to single administrative domains. In this architecture, an application can assume that a packet with a given destination address will eventually be forwarded toward that destination, but little else.

A transport-layer protocol such as TCP can provide reliability over this best-effort service, and a protocol above the network layer, such as Transport Layer Security (TLS) [RFC8446], can authenticate the remote endpoint. However, little, if any, explicit information about the path is available to the endpoints, and any assumptions made about that path often do not hold. These sometimes have serious impacts on the application, as in the case with BGP hijacking attacks.

By contrast, in a path-aware internetworking architecture, endpoints can select or influence the path(s) through the network used by any given packet or flow. The network and transport layers explicitly expose information about the path or paths available to the endpoints and to the applications running on them, so that they can make this selection. The Application-Layer Traffic Optimization (ALTO) protocol [RFC7285] can be seen as an example of a path-awareness approach implemented in transport-layer terms on the present Internet protocol stack.

Path selection provides explicit visibility and control of network treatment to applications and users of the network. This selection is available to the application-, transport-, and/or network-layer entities at each endpoint. Path control at the flow and subflow level enables the design of new transport protocols that can leverage multipath connectivity across disjoint paths through the Internet, even over a single physical interface. When exposed to applications, or to end users through a system configuration interface, path control allows the specification of constraints on the paths that traffic should traverse, for instance to confound passive surveillance in the network core [RFC7624].

We note that this property of "path awareness" already exists in many Internet-connected networks within single domains. Indeed, much of the practice of network engineering using encapsulation at layer 3 can be said to be "path aware" in that it explicitly assigns traffic at tunnel endpoints to a given path within the network. Path-aware internetworking seeks to extend this awareness across domain boundaries without resorting to overlays, except as a transition technology.

This document presents a snapshot of open questions in this space that will need to be answered in order to realize a path-aware internetworking architecture; it is published to further frame discussions within and outside the Path Aware Networking Research Group, and is published with the rough consensus of that group.

1.1. Definitions

For purposes of this document, "path-aware networking" describes endpoint discovery of the properties of paths they use for communication across an internetwork, and endpoint reaction to these properties that affects routing and/or data transfer. Note that this can and already does happen to some extent in the current Internet architecture; this definition expands current techniques of path discovery and manipulation to cross administrative domain boundaries and up to the transport and application layers at the endpoints.

Expanding on this definition, a "path-aware internetwork" is one in which endpoint discovery of path properties and endpoint selection of paths used by traffic exchanged by the endpoint are explicitly supported regardless of the specific design of the protocol features that enable this discovery and selection.

A "path", for the purposes of these definitions, is abstractly defined as a sequence of adjacent path elements over which a packet can be transmitted, where the definition of "path element" is technology dependent. As this document is intended to pose questions rather than answer them, it assumes that this definition will be refined as part of the answer to the first two questions it poses about the vocabulary of path properties and how they are disseminated.

Research into path-aware internetworking covers any and all aspects of designing, building, and operating path-aware internetworks or the networks and endpoints attached to them. This document presents a collection of research questions to address in order to make a path-aware Internet a reality.

2. Questions

Realizing path-aware networking requires answers to a set of open research questions. This document poses these questions as a starting point for discussions about how to realize path awareness in the Internet and to direct future research efforts within the Path Aware Networking Research Group.

2.1. A Vocabulary of Path Properties

The first question: how are paths and path properties defined and represented?

In order for information about paths to be exposed to an endpoint, and for the endpoint to make use of that information, it is necessary to define a common vocabulary for paths through an internetwork and properties of those paths. The elements of this vocabulary could include terminology for components of a path and properties defined for these components, for the entire path or for subpaths of a path. These properties may be relatively static, such as the presence of a given node or service function on the path, as well as relatively dynamic, such as the current values of metrics such as loss and latency.

This vocabulary and its representation must be defined carefully, as its design will have impacts on the properties (e.g., expressiveness, scalability, and security) of a given path-aware internetworking architecture. For example, a system that exposes node-level information for the topology through each network would maximize information about the individual components of the path at the endpoints, at the expense of making internal network topology universally public, which may be in conflict with the business goals of each network's operator. Furthermore, properties related to individual components of the path may change frequently and may quickly become outdated. However, aggregating the properties of individual components to distill end-to-end properties for the entire path is not trivial.

2.2. Discovery, Distribution, and Trustworthiness of Path Properties

The second question: how do endpoints and applications get access to accurate, useful, and trustworthy path properties?

Once endpoints and networks have a shared vocabulary for expressing path properties, the network must have some method for distributing those path properties to the endpoints. Regardless of how path property information is distributed, the endpoints require a method to authenticate the properties in order to determine that they originated from and pertain to the path that they purport to.

Choices in distribution and authentication methods will have impacts on the scalability of a path-aware architecture. Possible dimensions in the space of distribution methods include in band versus out of band, push versus pull versus publish subscribe, and so on. There are temporal issues with path property dissemination as well, especially with dynamic properties, since the measurement or elicitation of dynamic properties may be outdated by the time that information is available at the endpoints, and interactions between the measurement and dissemination delay may exhibit pathological behavior for unlucky points in the parameter space.

2.3. Supporting Path Selection

The third question: how can endpoints select paths to use for traffic in a way that can be trusted by the network, the endpoints, and the applications using them?

Access to trustworthy path properties is only half of the challenge in establishing a path-aware architecture. Endpoints must be able to use this information in order to select paths for specific traffic they send. As with the dissemination of path properties, choices made in path-selection methods will also have an impact on the trade-off between scalability and expressiveness of a path-aware architecture. One key choice here is between in-band and out-of-band control of path selection. Another is granularity of path selection (whether per packet, per flow, or per larger aggregate), which also has a large impact on the scalability/expressiveness trade-off. Path selection must, like path property information, be trustworthy, such that the result of a path selection at an endpoint is predictable. Moreover, any path-selection mechanism should aim to provide an outcome that is not worse than using a single path or selecting paths at random.

Path selection may be exposed in terms of the properties of the path or the identity of elements of the path. In the latter case, a path may be identified at any of multiple layers (e.g., routing domain identifier, network-layer address, higher-layer identifier or name, and so on). In this case, care must be taken to present semantically useful information to those making decisions about which path(s) to trust.

2.4. Interfaces for Path Awareness

The fourth question: how can interfaces among the network, transport, and application layers support the use of path awareness?

In order for applications to make effective use of a path-aware networking architecture, the control interfaces presented by the network and transport layers must also expose path properties to the application in a useful way, and provide a useful set of paths among which the application can select. Path selection must be possible based not only on the preferences and policies of the application developer, but of end users as well. Also, the path-selection interfaces presented to applications and end users will need to support multiple levels of granularity. Most applications' requirements can be satisfied with the expression of path-selection policies in terms of properties of the paths, while some applications may need finer-grained, per-path control. These interfaces will need to support incremental development and deployment of applications, and provide sensible defaults, to avoid hindering their adoption.

2.5. Implications of Path Awareness for the Transport and Application Layers

The fifth question: how should transport-layer and higher-layer protocols be redesigned to work most effectively over a path-aware networking layer?

In the current Internet, the basic assumption that at a given time all traffic for a given flow will receive the same network treatment and traverse the same path or equivalent paths often holds. In a path-aware network, this assumption is more easily violated. The weakening of this assumption has implications for the design of protocols above any path-aware network layer.

For example, one advantage of multipath communication is that a given end-to-end flow can be "sprayed" along multiple paths in order to confound attempts to collect data or metadata from those flows for pervasive surveillance purposes [RFC7624]. However, the benefits of this approach are reduced if the upper-layer protocols use linkable identifiers on packets belonging to the same flow across different paths. Clients may mitigate linkability by opting to not reuse cleartext connection identifiers, such as TLS session IDs or tickets, on separate paths. The privacy-conscious strategies required for effective privacy in a path-aware Internet are only possible if higher-layer protocols such as TLS permit clients to obtain unlinkable identifiers.

2.6. What is an Endpoint?

The sixth question: how is path awareness (in terms of vocabulary and interfaces) different when applied to tunnel and overlay endpoints?

The vision of path-aware networking articulated so far makes an assumption that path properties will be disseminated to endpoints on which applications are running (terminals with user agents, servers, and so on). However, incremental deployment may require that a path-aware network "core" be used to interconnect islands of legacy protocol networks. In these cases, it is the gateways, not the application endpoints, that receive path properties and make path selections for that traffic. The interfaces provided by this gateway are necessarily different than those a path-aware networking layer provides to its transport and application layers, and the path property information the gateway needs and makes available over those interfaces may also be different.

2.7. Operating a Path-Aware Network

The seventh question: how can a path-aware network in a path-aware internetwork be effectively operated, given control inputs from network administrators, application designers, and end users?

The network operations model in the current Internet architecture assumes that traffic flows are controlled by the decisions and policies made by network operators as expressed in interdomain and intradomain routing protocols. In a network providing path selection to the endpoints, however, this assumption no longer holds, as endpoints may react to path properties by selecting alternate paths. Competing control inputs from path-aware endpoints and the routing control plane may lead to more difficult traffic engineering or non-convergent forwarding, especially if the endpoints' and operators' notion of the "best" path for given traffic diverges significantly. The degree of difficulty may depend on the fidelity of information made available to path-selection algorithms at the endpoints. Explicit path selection can also specify outbound paths, while BGP policies are expressed in terms of inbound traffic.

A concept for path-aware network operations will need to have clear methods for the resolution of apparent (if not actual) conflicts of intent between the network's operator and the path selection at an endpoint. It will also need a set of safety principles to ensure that increasing path control does not lead to decreasing connectivity; one such safety principle could be "the existence of at least one path between two endpoints guarantees the selection of at least one path between those endpoints."

2.8. Deploying a Path-Aware Network

The eighth question: how can the incentives of network operators and end users be aligned to realize the vision of path-aware networking, and how can the transition from current ("path-oblivious") to path-aware networking be managed?

The vision presented in the introduction discusses path-aware networking from the point of view of the benefits accruing at the endpoints, to designers of transport protocols and applications as well as to the end users of those applications. However, this vision requires action not only at the endpoints but also within the interconnected networks offering path-aware connectivity. While the specific actions required are a matter of the design and implementation of a specific realization of a path-aware protocol stack, it is clear that any path-aware architecture will require network operators to give up some control of their networks over to endpoint-driven control inputs.

Here, the question of apparent versus actual conflicts of intent arises again: certain network operation requirements may appear essential but are merely accidents of the interfaces provided by current routing and management protocols. For example, related (but adjacent) to path-aware networking, the widespread use of the TCP wire image [RFC8546] in network monitoring for DDoS prevention appears in conflict with the deployment of encrypted transports, only because path signaling [RFC8558] has been implicit in the deployment of past transport protocols.

Similarly, incentives for deployment must show how existing network operation requirements are met through new path selection and property dissemination mechanisms.

The incentives for network operators and equipment vendors need to be made clear, in terms of a plan to transition [RFC8170] an internetwork to path-aware operation, one network and facility at a time. This plan to transition must also take into account that the dynamics of path-aware networking early in this transition (when few endpoints and flows in the Internet use path selection) may be different than those later in the transition.

Aspects of data security and information management in a network that explicitly radiates more information about the network's deployment and configuration, and implicitly radiates information about endpoint configuration and preference through path selection, must also be addressed.

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