Incentivizing Stable Path Selection in Future Internet Architectures

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ABSTRACT

By delegating path control to end-hosts, future Internet architectures offer flexibility for path selection. However, a concern arises that the distributed routing decisions by end-hosts, in particular load-adaptive routing, can lead to oscillations if path selection is performed without coordination or accurate load information. Prior research has addressed this problem by devising local path-selection policies that lead to global stability. However, little is known about the viability of these policies in the Internet context, where selfish end-hosts can deviate from a prescribed policy if such a deviation is beneficial from their individual perspective. In order to achieve network stability in future Internet architectures, it is essential that end-hosts have an incentive to adopt a stability-oriented path-selection policy.

In this work, we perform the first incentive analysis of the stability-inducing path-selection policies proposed in the literature. Building on a game-theoretic model of end-host path selection, we show that these policies are in fact incompatible with the self-interest of end-hosts, as these strategies make it worthwhile to pursue an oscillatory path-selection strategy. Therefore, stability in networks with selfish end-hosts must be enforced by incentive-compatible mechanisms. We present two such mechanisms and formally prove their incentive compatibility.

Keywords

Path-aware Internet, path selection, traffic oscillation, game theory, mechanism design, network stability

INTRODUCTION

The past 20 years of research on next-generation Internet architectures have shown the benefits of path awareness and path control for end-hosts, and multiple path-aware network architectures have been proposed. Many of these architectures, including RON [1], Platypus [16], MIRO [19], Pathlets [8], Segment Routing [5], and SCION [2], allow end-hosts to select the inter-domain paths over which their data packets are forwarded. One principal argument for such path control is that it enables load-adaptive routing, i.e., allows the end-hosts to avoid congested links, and should therefore lead to a relatively even traffic distribution. However, load-adaptive routing creates new challenges, in particular the introduction of instabilities under certain conditions. Instability due to load-adaptive routing typically appears in the form of *oscillations*, i.e., periodic up- and downswings of link utilization, leading to a large variance of the traffic load in a short time span. According to the IETF, a central obstacle to deployment of path-aware network architectures are 'oscillations based on feedback loops, as hosts move from path to path' [3]. Indeed, such oscillations can be shown to occur if path-selection decisions are taken on the basis of outdated load information [7, 18], which is the case in any real system.

Such oscillations are undesirable for many reasons, both from the perspective of end-hosts and network operators. If oscillation occurs when a link is near its capacity limit, a danger of queue build-up, jitter, and, as a result, unpredictable performance emerges. Moreover, oscillation temporarily leads to a heavily skewed load distribution over paths, causing higher overall queuing latency than with a more equal traffic distribution. Due to the large variance of the load level over time, network operators have to perform substantial overprovisioning of link capacities, which is undesirable from a business perspective. Moreover, oscillation of inter-domain traffic imposes additional overhead for intra-domain traffic engineering (e.g., MPLS circuit setup), as oscillating inter-domain flows may constantly switch between inter-AS interfaces. From the end-host perspective, oscillation causes packet loss and thus forces the congestion-control algorithms to recurring restarts, negatively affecting throughput.

To avoid these damaging effects, researchers have devised numerous schemes to guarantee stability of load-adaptive routing. However, to the best of our knowledge, no scheme so far has aimed at providing stability in Internet architectures with end-host path control. Several systems have been designed under the assumption of network-based path selection, i.e., hop-by-hop forwarding according to decisions taken by intermediate routers [6, 9, 13, 14]. These systems achieve convergence by appropriately adjusting how much traffic is forwarded to each next hop towards a destination and cannot be used if packets must be sent along paths selected by end-hosts. Other systems allow end-point path selection, but are targeted at an intra-domain context where the end-points (typically ingress and egress routers) are under the control of a network operator [4, 7, 10, 11, 12, 15]. In an intra-domain context, network operators are able to prescribe arbitrary path-selection procedures that generate stability. Conversely, in an inter-domain context, the end-points are not under control of network operators and can thus not be forced to adopt a non-oscillatory path-selection strategy. Instead, as end-hosts must be assumed to be selfish, they can only be expected to adopt path-selection strategies that optimize performance *from their individual perspective*.

OUR CONTRIBUTION

This paper revisits the theoretical study of the dynamic effects of end-point path selection, for the first time focusing the analysis on inter-domain networks where the end-points are selfish and uncontrolled. We present a game-theoretic model that allows us to investigate which path-selection strategies (PSS) will be adopted by selfish end-hosts. In particular, we introduce the notion of equilibria to path-selection strategies (*PSS equilibria*). Based on this model, we show that the non-oscillatory path-selection strategies traditionally proposed in the literature on stable source routing [4, 7, 10, 11, 12, 15] are incompatible with the self-interest of end-hosts and thus do not form PSS equilibria. Assuming that such non-oscillatory path-selection strategies are universally adopted, an end-host can increase its utility by deviating in favor of a strategy that is oscillatory.

These results indicate that stability in load-adaptive routing over multiple domains cannot be achieved by exclusively relying on end-hosts' path-selection behavior. Instead, network operators have to *incentivize* end-hosts to adopt one of the well-known convergent path-selection strategies with *stabilization mechanisms*. These mechanisms have to be *incentive-compatible*, i.e., the mechanisms must create an incentive structure such that it is in an end-host's self-interest to adopt a non-oscillatory path-selection strategy. In this work, we leverage insights from mechanism design to develop two such stabilization mechanisms, namely the *Flow-Loyalty Oscillation-Suppression System* (FLOSS) and the *Computation-Requiring Oscillation Suppression System* (CROSS), and formally prove their incentive compatibility. While these mechanisms build on existing insights from intra-domain traffic engineering, their methods of incentivization represent a novel approach to achieve stability in inter-domain networks with load-adaptive routing. While FLOSS requires end-hosts to make *reservations* for the paths they intend to use, which are only granted to a subset of applicants, CROSS imposes a *computational cost* on switching between paths. To complement our mainly theoretical work, we also discuss how our findings could be practically applied.

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