An Axiomatic Perspective on the Performance Effects of End-Host Path Selection

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ABSTRACT

In various contexts of networking research, end-host path selection has recently regained momentum as a design principle. While such path selection has the potential to increase performance and security of networks, there is a prominent concern that it could also lead to network instability (i.e., flow-volume oscillation) if paths are selected in a greedy, load-adaptive fashion. However, the extent and the impact vectors of instability caused by path selection are rarely concretized or quantified, which is essential to discuss the merits and drawbacks of end-host path selection.

In this work, we investigate the effect of end-host path selection on various metrics of networks both qualitatively and quantitatively. To achieve general and fundamental insights, we leverage the recently introduced axiomatic perspective on congestion control and adapt it to accommodate joint algorithms for path selection and congestion control, i.e., *multi-path congestion-control* protocols. Using this approach, we identify equilibria of the multi-path congestion-control dynamics and analytically characterize these equilibria with respect to important metrics of interest in networks (the "axioms") such as efficiency, fairness, and loss avoidance. We analyze how these axiomatic ratings for a general network change compared to a scenario without path selection, thereby obtaining an interpretable and quantitative formalization of the performance impact of end-host path-selection. Finally, we show that there is a fundamental trade-off in multi-path congestion-control protocol design between efficiency, stability, and loss avoidance on one side and fairness and responsiveness on the other side.

Keywords

Path selection, congestion control, traffic oscillation

INTRODUCTION

Path selection performed by end-points is a promising approach to improve efficiency, security, and robustness of networks in their various forms: To name a few examples, solutions based on end-point path selection have been proposed for routing on multiple optimality criteria, multi-tenant data centers, mobile ad-hoc networks, LEO satellite networks, intra-domain forwarding, and inter-domain forwarding [1]. However, proposals based on end-host path selection often encounter a stability concern: researchers have identified the problem that uncoordinated path-selection decisions by end-points may lead to persistent *oscillation*, i.e., an alternating grow-and-shrink pattern of traffic volumes. The risk of oscillation represents an obstacle to deployment of path-aware networks and gives rise to schemes that try to avoid oscillation. While there is a rich literature presenting solutions for oscillation suppression, relatively little is known about *how exactly* and *by how much* instability from path selection deteriorates network performance.

In this work, we therefore qualify and quantify the effects of oscillatory path selection on various metrics of a network. To tackle this challenge, we must take into account that end-points in real path-aware networks employ algorithms which jointly perform path selection and congestion control (CC), i.e., multi-path congestion-control (MPCC) algorithms. In this work, we will focus on MPCC algorithms that are inspired by greedy, myopic path-selection behavior and thus simultaneously produce and react to oscillation. Furthermore, we require an analytical approach that (i) captures the congestion-window fluctuations that represent the oscillation, and (ii) is general enough to deliver fundamental insights into the nature of CC-assisted end-host path selection. We argue that a so-called *axiomatic* approach recently initiated by Zarchy et al. [3] offers both the right analytical resolution and the required generality for the question at hand. This approach is axiomatic in a sense borrowed from economics and game theory, where properties with obvious desirability (e.g., the acyclicity of preferences or the fairness of a bargaining outcome) are formulated as axioms. Zarchy et al. apply this approach to congestion control by capturing desirable properties of CC protocols such as efficiency, fairness, and stability in axioms. The approach allows to analytically rate protocols with respect to these axioms and highlight the fundamental trade-offs between them.

APPROACH

In our work, we further extend Zarchy et al.'s model to a multi-path context with the goal of characterizing fundamental properties of joint algorithms for path selection and CC. Hence, we develop a model that is able to cap-

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ture both path-selection dynamics and congestion-window fluctuations. Since the flow dynamics in this model are determined by a stochastic process that is hard to analyze, we focus our analysis on large-scale systems with many senders, which allows an approximation of the stochastic process by a deterministic process based on the law of large numbers.

For these deterministic flow dynamics, we identify and formalize different classes of dynamic equilibria to which the flow dynamics can be expected to converge exponentially fast. These dynamic equilibria are given by recurring patterns of usage for a given path, where the usage is characterized by both the number of senders using the path and the traffic load on the path. We distinguish *lossless equilibria*, where the equilibrium load level is below the bottleneck-link capacity, and *lossy equilibria*, which include recurrent loss.

In our paper, we rate these dynamic equilibria with respect to a number of performance metrics (the axioms), which are inspired by the recently developed axiomatic approach to CC [3], but extended to accommodate path selection. For example, the following axiom relates to efficiency:

Axiom 1. ***Efficiency.*** *An MPCC protocol is **ϵ-efficient** if under universal adoption of this protocol, the bottleneck utilization $\hat{f}_\pi(t)/C$ of every path π with capacity C is never lower than a share ϵ after some time t':*

$$\exists t'. \quad \forall t \geq t',\ \pi \in \Pi. \quad \frac{\hat{f}_\pi(t)}{C} \geq \epsilon \tag{1}$$

Larger values of ϵ are better, and we consider an ϵ-efficient protocol optimal if $\epsilon \geq (C-s)/C$, where s is the buffer size.

INSIGHTS

These axiom metrics are then used to generate two categories of insights. The first category of insights concerns the performance of MPCC protocols for varying protocol parameters, namely the migration rate m, the congestion-window reset r upon path switch. and the congestion-window growth function α. To be precise, the dynamic equilibria induced by an MPCC protocol change in dependence of these parameters, and the axiomatic scores of these dynamic equilibria change accordingly. Hence, the insights from the first category describe how performance in a network with end-host path selection is affected by parameter changes, and how different axiom metrics must be traded off when choosing MPCC parameters:

Insight 1. ***No trade-off between efficiency, convergence and loss avoidance:*** *Through appropriate protocol tuning, the metrics efficiency, loss avoidance, and convergence can be simultaneously optimized. Hence, there is no trade-off between these properties in theory.*

Insight 2. ***Trade-off with fairness and responsiveness:*** *There is, however, a fundamental trade-off between the above metrics and the fairness and the responsiveness of a MPCC protocol. In particular, higher responsiveness makes a protocol less efficient, but more fair.*

The second category of insights concerns the performance effects of introducing path selection into a network without path selection. These insights rely on a comparison of the axiom metrics of a given CC protocol with the axiom metrics of an MPCC protocol, which is based on the same CC protocol, but additionally incorporates path switching behavior. Such a comparative analysis yields the following surprising insight:

Insight 3. ***Effects of introducing end-host path selection:*** *Oscillation from path selection is not necessarily harmful. Instead, oscillation stemming from moderate path migration can even improve network performance metrics compared to a network where no path selection is possible.*

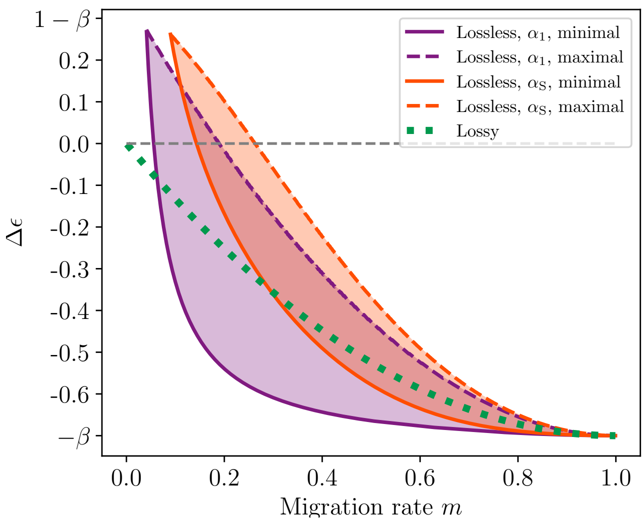

Figure 1: Change in efficiency level ϵ due to the introduction of end-host path selection (Multiplicative decrease β on loss, window-growth functions α_1 and α_S, cf. full paper).

Figure 1 illustrates this insight at the example of the efficiency axiom: For high migration rates, the change $\Delta\epsilon$ in the efficiency metric ϵ is negative for all equilibrium types, i.e., path selection deteriorates efficiency compared to the absence of path selection. Also for very low migration rates, lossy equilibria are the only viable equilibria, which consistently reduce the efficiency compared to a scenario without path selection. For moderate migration rates, however, this efficiency change may be positive, meaning that the network experiences higher efficiency if unstable path selection is applied than if path selection is not allowed.

The full version of this paper with additional insights has been published in *Performance Evaluation (PEVA)* [2].

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REFERENCES

[1] D. Barrera, L. Chuat, A. Perrig, R. M. Reischuk, and P. Szalachowski. The SCION Internet architecture. *Communications of the ACM*, 2017.

[2] S. Scherrer, M. Legner, A. Perrig, and S. Schmid. An axiomatic perspective on the performance effects of end-host path selection. *Performance Evaluation*, page 102233, 2021.

[3] D. Zarchy, R. Mittal, M. Schapira, and S. Shenker. Axiomatizing congestion control. *Proceedings of the ACM Conference on Measurement and Analysis of Computing Systems (SIGMETRICS)*, 3(2):1–33, 2019.