

A Mutualistic Resource Pooling Architecture

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ABSTRACT

Parallelism pervades the Internet. Paradoxically for a network geared towards robustness and efficiency, exploring this increasing path diversity has remained elusive. We defend that this inability to progress beyond a single path paradigm is due to an inflexible resource sharing model, rather than a lack of routing solutions. The current architecture predates the rise of the commercial network and as such did not anticipate the need for networks to exert control in order to protect their own resources from misuse. The ensuing tussle surrounding resource sharing has constricted resource pooling into being redefined by stakeholders according to their own needs, often at the expense of others.

In this paper we debate the often conflicting approaches to resource pooling and present PREFLEX, an architecture where edge networks and hosts both share the burden and reap the rewards of balancing traffic over multiple paths. By making apparent network needs and transport expectations, PREFLEX provides a mutualistic framework where congestion control and traffic engineering can both coexist and evolve independently.

1. INTRODUCTION

While the Internet has become evermore interconnected, exploring path diversity has been relegated to an afterthought in an architecture modeled around assumptions that no longer stand. Single-path forwarding as a paradigm arose not as a guiding principle, but as a natural aversion towards increasing both the complexity and cost of a resource starved network.

Engineering for scarcity has propelled the Internet to

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an unprecedented scale, but problems arise when what was otherwise scarce becomes plentiful. Protocols designed to be bit conservative at the expense of latency have become technological anachronisms as bandwidth costs continue to plummet. Similarly, the notion of a router as a device merely capable of forwarding packets has long been obsolete as Moore's law continues to pave the way for greater functionality within the network. Network address translation (NAT), deep packet inspection (DPI) or performance enhancing proxies (PEP) are all examples that when it comes to drawing a boundary between network and transport, the line begins to blur [1].

Furthermore, parallelism seems to be a dominant trend at every level of the Internet architecture as a cost-effective means of increasing both performance and robustness. At the inter-domain level, the AS graph is becoming flatter and more highly interconnected [2]. Within domains, the sheer complexity of managing paths has led to the streamlined design and deployment of MPLS [3], implementing a fully fledged layer in its own right. At the edges the rise in multi-homing continues to increase the strain on an already overloaded routing architecture. Even within network components, parallelism is such that packet re-ordering can no longer be considered pathological [4].

Given these trends, one would expect the ability to pool traffic across such emergent path diversity to have become a network primitive. In reality, each stakeholder in the Internet architecture seems to balance traffic according to their needs while attempting to remain inconspicuous to others. At best, this interaction between stakeholders can be seen as a form of commensalism, where one entity can extract benefits while others remain unaffected. At worse, the competitive nature of the tussle that ensues can spiral into a situation where few profit.

In this paper we investigate the nature of this antagonism between network and endpoints and reflect on how the Internet can accommodate the needs of both. We then introduce PREFLEX, Path RE-Feedback with Loss EXposure, an architecture for balancing conges-

tion which foments mutualism between end-hosts and edge network providers.

2. A HISTORY OF ANTAGONISM

The ability to evolve beyond single path forwarding has often been misdiagnosed primarily as a routing challenge. The subject is frequently revisited with varying approaches [5, 6, 7, 8]. Despite this, multipath routing has remained a pipe dream for end-hosts. The common trait all these proposals share is a failure to identify the tussle over resource control as the primary obstacle in moving towards the use of multiple concurrent paths.

The Internet architecture places resource control at the edges, in what can be viewed as an instance of the end-to-end principle [9]. This represented a fundamental paradigm shift, ultimately conferring the scalability which fueled the growth of the Internet. While unilateral control of a network resource by hosts was already polemic in an academic research network, with the rise of the commercial Internet this notion has slowly been set aside by stakeholders intent on exerting control over their own networks.

Network operators have now become accustomed to inspect, shape and throttle traffic in an attempt to override resource sharing as implicitly performed by TCP. A common cause for such behaviour could derive from the perceived freeriding made possible by TCP, whereby a minority of users can gain an disproportionate amount of bandwidth, with detrimental effects for the majority of users. In a broader sense, networks attempt to reflect their own objectives and concerns. Because this was not contemplated when designing our resource sharing model the subsequent violations of the end-to-end principle say more about the limitations of the current architecture than the ill intent of the perpetrators.

Nowhere is this more apparent than in traffic engineering. Network operators rely heavily on traffic engineering to balance utilization over long timescales in an attempt to reduce costs by making efficient use of available paths. Since information at the network layer is limited, traffic engineering optimizes for the wrong metric - utilization - in detriment of the congestion it may be causing. Additionally, this optimization is typically executed offline, and re-computed over long timescales to minimize the impact to higher layers and ensure stability. The limiting assumption is that traffic patterns are exogenous. In reality, hosts will often find means of adapting to network conditions, such as establishing overlay networks. This resulting shift in behaviour may in turn conflict with the concurrent traffic engineering process, which will have to readjust to a substantially different traffic matrix in a next iteration. This antagonistic cycle leaves traffic engineering as a whole stuck in a rut, unable to adapt too often, out of fear of disrupting transport protocols, and unable to adapt often

enough in order to react to changes in traffic.

The inability to reach a compromise between network interests and transport layer expectations has severely limited network-assisted traffic balancing despite a strong commercial interest. Equal-Cost Multipath (ECMP), a seemingly simple solution for balancing traffic over similar paths, has fallen out of grace [10]. Relevant research in dynamic traffic engineering, such as MATE [11] or TeXCP [12], has trod new footsteps on old grounds, continuing to focus on utilization as the sole metric for performance.

In stark contrast with traffic engineering, the interest in the use of congestion control to balance traffic across paths has gained significant traction, particularly in the wake of seminal contributions [13], [14] which provide the theoretical basis for much of the standardization effort behind Multipath TCP [15] (MPTCP). This alone however is unlikely to overcome significant architectural shortcomings. For one, path diversity is opaque to end-hosts, which restricts deployment of MPTCP to multihomed hosts. Given networks are already concerned with TCP's ability to share bandwidth in its single path incarnation, it remains unlikely ISPs will consider making path diversity visible to end-hosts. Additionally, it is not yet clear what proportion of traffic MPTCP will encompass, or what proportion of MPTCP traffic would be required to maintain a network consistently balanced. Finally, flows which cannot be split into subflows, because they are too short or for other motives such as security concerns, will remain restricted to choosing a default path, rather than a best path.

Neither congestion control or traffic engineering alone seem fully capable of bridging the divide between networks and end-hosts. The discussion around the relative merits of both is often manichean and erroneously simplified as a conflict between advocates and opposers of the end-to-end principle. This entirely misses the point. The concern should not revolve around whether an approach is right or wrong, but whether it is applicable within a given context or not. The recognition of the commercial network as a fundamental stakeholder is intrinsic to the evolvability of the current architecture. In the absence of such recognition, the gulf between our perception of how the Internet works and how it works in practice will only widen. If we regard both traffic engineering and congestion control as different sides of the same coin, it is our duty to provide the architectural underpinnings for both to evolve independently while not foregoing cooperation.

Recent research in resource sharing has suggested that much of the misalignment between network and transport derives from the lack of accountability for congestion. While previous work had modelled and analyzed the broken incentive structure subjacent to forwarding traffic from an economic perspective, work on

re-feedback [16] and congestion exposure [] pioneered a practical means of alleviating the tussle surrounding resource sharing. In particular, congestion exposure advocates the use of congestion volume, rather than throughput or traffic volume, as the by-product by which the impact of traffic should be assessed. We build on this approach and present a concept for a joint, mutualistic architecture for congestion control and traffic engineering.

3. PREFLEX ARCHITECTURE

The PREFLEX (Path RE-Feedback with Loss EXposure) architecture can be split into two independent components. At the network, we define a mechanism for path re-feedback (PREF), whereby stub domains can signal a preferred path to end-hosts according to local policy or perceived path quality. At the end-hosts we specify a transport agnostic protocol for loss exposure (LEX), which explicitly marks packets within a flow in order to signal path loss back to the network.

While functionally separate, in practice both components work in tandem. The use of loss exposure, while executed by hosts, provides network operators with a practical means of policing congestion and feedback on end-to-end path loss. Conversely, with path re-feedback hosts are allowed access to paths selected by the network. Together, PREFLEX bridges the divide between network and transport layers in order to balance congestion, rather than load, over the multiple paths typically available solely to edge networks.

3.1 Loss Exposure

We propose a simple protocol for revealing loss, LEX, which not only borrows heavily from re-ECN, a protocol for congestion exposure, but which can coexist and serve as a stepping stone for the deployment of the latter. By revealing information currently confined to the transport layer down to the network, we are both deterring the need for the network to inspect higher level protocol headers and correcting the information asymmetry that currently afflicts networks, who know less about the quality of service they provide than their customers.

3.1.1 From flow to flowlet

The first change proposed for LEX is to have end-hosts mark, at the network layer, packets belonging to flows where feedback has not been established. This typically corresponds to the first packet exchange in a flow, such as SYN packets in TCP, but may also include the first packet after a significant idle period, a keep-alive packet or a renewed attempt at a retransmission after successive retransmit timeouts in the case of network failure. Within LEX, as with re-ECN, such packets are labelled FNE (Feedback Not Established).

The signalling of such packets has many practical implications. For one, from simply inspecting the IP header, networks are made aware of the first of a succession of similar packets, which poses significant advantages in allocating state in middleboxes, whether it be to perform admission control, policing or traffic shaping. All of the above are possible by inspecting TCP, but we attempt here to make apparent an architectural *trompe d’oeil*: that a connectionless layer should be oblivious to connection setup. By making such information explicit at the IP layer we are alleviating in some measure the need for consistent violation of layering by network equipment, or hopefully circumscribing such practices to a small subset of packets.

Additionally, the concept of a transport flow, which establishes an association between two endpoints, is decoupled from the concept of a network flow, which will henceforth be referred to as a flowlet [17]. We define a flowlet as a stream of packets which the endhost expects to follow the same network path. The same transport flow may be composed of a single flowlet, parallel flowlets, or a succession of different flowlets. As we shall see later, this feature is particularly advantageous for balancing traffic as flowlets provide a finer granularity than existing flows, as well as allowing flows to quickly switch path without breaking the transport session.

3.1.2 Echoing loss

Once feedback has been established, hosts adjust their sending rate in response to implicit congestive signals such as delay or packet loss, or explicit signals such as ECN. Protocols for congestion exposure, such as re-ECN, mark outgoing packets according to the explicit congestion marking received from the network. As such, IP packets would carry two congestion markings. The first indicating the congestion experienced so far and the second indicating the end-to-end congestion experienced by the host in the previous RTT. With this re-feedback of congestion markings, networks are able to estimate rest-of-path congestion, which is an important metric for keeping customers accountable for the congestion they cause and providers accountable for the service they provide.

We specify a simplified form of congestion exposure which uses the implicit information contained in losses as opposed to relying on the widespread deployment of congestion notification. Where packet loss does arise, LEX requires that hosts mark their respective retransmits with a Loss Experienced (LE_{Ex}) codepoint. The drawback of this approach is that only the end-to-end congestion can be estimated from a stream of packets, which implies that traffic can only be reliably aggregated close to the source, and effectively policed close to the receiver. As we shall see later, because the focus of PREFLEX is balancing congestion at a stub domain

Codepoint	Meaning
Not-LECT	Not Loss Exposure Capable Transport
LECT	Loss Exposure Capable Transport
LEx	Loss Experienced
FNE	Feedback Not Established

Table 1: LEX codepoints and respective meaning.

this limitation is not significant.

If run as a complement of re-ECN, three of the four codepoints in table 1 are potentially shared, in which case only the loss experienced codepoint has to be added to the re-ECN specification. For routers along the path, an accurate estimate of the end-to-end path loss can be obtained by simply dividing the sum of bytes marked with the loss experienced codepoint, by the total traffic marked as either LECT or LEx. Additionally, one could envision a preferential dropping mechanism which prioritizes retransmits.

3.2 Path Re-feedback

For networks, the most significant hurdle in adopting multiple paths for a single destination has not been the selection process. Instead, the main difficulty resides in assigning packets to paths. Since balancing traffic at a packet granularity has severe repercussions for the transport layer, network operators have typically resorted to splitting prefixes. Increasingly, networks have also been able to afford the cost of keeping flow state in an attempt to balance traffic at a finer granularity.

Neither of these approaches are strictly necessary in a mutualistic architecture. Since we require that hosts be made aware of the path packets take, we can push flow state towards the edge by placing the responsibility for assigning packets to paths at the endpoints. In such a case, a network only needs to perform path selection according to local policy and pass the information onto the end-host.

For this purpose, we use FNE packets, as defined in LEX, to act as network triggers for path selection. An ISP or stub domain, upon detecting an incoming FNE packet, selects a preferred outgoing path based on the reverse lookup of the source address, and marks the packet with a path identifier. For IPv4, a possible location for such marking to occur could be within the Diffserv field, where a set of codepoints are reserved for local use. On receiving an FNE packet containing a path identifier, a sender should tag all subsequent packets using the same identifier in order to ensure a flowlet will traverse the selected egress at the stub domain.

A subtle implication of triggering path selection based on incoming packets, rather than resorting to out-of-band signalling for example, is that path selection becomes receiver driven. The responsibility for defining a

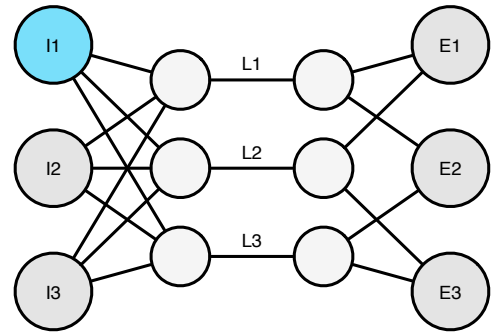


Figure 1: Simulation topology.

strategy on when and how often to attempt a path request lays firmly with the stakeholder who extracts the most benefit. The flipside is that because FNE packets require additional network intervention, whether for selecting a new path or setting up state, networks may rate limit the amount of FNE packets they receive in order to protect themselves from overload. This is the current line of thinking in re-ECN, where FNE packets are used to set state in congestion policers.

4. BALANCING BY PREFLEX

5. CONCLUSIONS

We have broadly described an architecture which shares the responsibility for resource pooling between endhosts and edge networks, but does not explicitly dictate an outcome. PREFLEX has been designed to take into account the inevitable tussle which will occur between both, and we envisage use cases where control over resource pooling could feasibly shift entirely in one direction or the other.

At its most liberal, PREFLEX enables resource pooling to be entirely performed by end-hosts. At its most conservative, PREFLEX affords edge network providers more fine-grained control over traffic than ever before. Between either extreme, the resulting mutualistic architecture offers greater transparency, control and robustness by realigning the interface between network and transport in order to accommodate the needs of both.

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