Over the past few years, Internet access speeds of organizations such as enterprises and educational institutions have improved quite significantly—from under 1.5Mbps to over 100Mbps. However, this higher-speed connectivity is still ineffective at providing end-users with good download performance and robustness from service interruptions. In fact, the Internet experience of users in these end-networks is often no better than what they observe at home using much lower-speed DSL connections.

In my thesis, I adopted a systematic, four-step approach to studying how to improve the Internet performance of well-connected end-networks, i.e., their resilience from service interruptions, their web response times, and Internet transfer speeds. First, I identified key links belonging to various carrier ISPs that could directly limit the Internet performance of the end-networks. Second, I studied how the end-networks can employ a clever route selection technique, called Multihoming Route Control, to avoid these performance bottlenecks and obtain much better Internet performance. Third, I investigated whether improvements in network link capacities over time will eliminate Internet performance problems altogether. I observed that the Internet’s topological structure and routing may, in fact, worsen the situation in the future. Lastly, I outlined simple changes to the topology of the Internet that can ensure robustness and efficiency in the functioning of the future network. I describe this work in greater detail below.

Wide-Area Internet Performance Bottlenecks

A key challenge in optimizing the Internet performance of well-connected end-networks is to identify the network links that constrain performance. For years, common knowledge about such wide-area bottleneck links was limited to folklore—these bottlenecks were widely believed to be confined to the edges of Internet domains (e.g., peering links), where link utilization is supposedly high.

In my work, I conducted the first quantitative study of the characteristics of typical wide-area bottleneck links. I probed a large number of paths between well-connected machines located at universities and routers inside various carrier ISPs. I developed a suite of tools to automatically identify and characterize bottleneck links along these paths. Using these tools, I found that bottleneck links with very low available bandwidth are prevalent in the wide-area Internet, especially inside or between small regional providers (IMC 2003\(^1\)). I also deduced significant correlations between the likelihood of wide-area links appearing as bottlenecks and the latencies of the links. Finally, I observed that contrary to the popular perception, wide-area bottlenecks are almost evenly split between peering and intra-domain links.

Multihoming Route Control

Although constrained bottlenecks exist in the wide-area Internet, the Internet’s rich topology makes it possible to “route around” them. Past studies for circumventing wide-area performance bottlenecks advocated using overlay routing. In this approach, end-points can route their traffic via intermediate “overlay” nodes deployed around the Internet. This helps end-points bypass the default routes determined by Internet’s routing protocol (BGP), and avoid bottlenecks along these routes.

In contrast, I believe that a much simpler approach called Multihoming Route Control can offer similar performance improvements as overlay routing. In this strategy, an end-network buys connectivity from a few different ISPs and intelligently schedules its traffic across the ISPs. The idea of multihoming route control was introduced a few years ago by commercial products such as RouteScience and SockEye. However, little was known about the true extent of the benefits of these products.

In my work, I quantified the potential benefits of multihoming route control in improving the Web download performance of Internet end-points, as well as their resilience to service interruptions. Using

\(^1\)Please refer to the list of publications in my CV for the complete reference.
Internet-scale experiments conducted in collaboration with Akamai Technologies, I showed that by multihoming to three providers, and intelligently scheduling transfers across the providers, an end-network could potentially improve its Internet response times and availability by up to 40%, relative to using a single provider connection (SIGCOMM 2003). Furthermore, I built a multihomed route control system to show that, in practice, route control products could employ very simple design and operational principles to extract nearly-optimal Internet performance from multihoming (USENIX 2004).

Since multihoming route control is BGP routing-compliant, it cannot provide nearly the same route selection flexibility as overlay routing. I showed that despite this seemingly limited flexibility, multihoming route control offers only marginally inferior Internet performance than overlay routing (SIGCOMM 2004). For example, the transfer speeds from multihoming to three providers are at most 10% inferior relative to overlay routing. This observation suggests that there is definite hope of extracting good performance from the BGP protocol, and therefore, it is unnecessary to replace BGP by a different protocol altogether.

**Performance Scaling in the Internet**

My work on multihoming showed that today’s routing protocols and topology can support good Internet performance. Over time, the Internet will grow in size and traffic volumes will increase. At the same time, ISPs will upgrade network link capacities to accommodate the growing traffic load. I observed that despite the improvement of link speeds in the future, the Internet’s topology and routing may, in fact, cause the load on certain links in the network to increase at a much faster rate than on others (PODC 2003). Such links could soon evolve into persistent bottlenecks, and, in turn, significantly limit future Internet performance. Specifically, I analyzed a simple model of the routing and topology of the Internet at an Autonomous System level (AS-level), and showed that the congestion at key links in the network may grow as poorly as $n^{1+\Omega(1)}$, where $n$ is the number of ASes.

This result implies that we may have to carefully alter the Internet’s topology and/or routing to improve the performance of the network. To this end, using large-scale simulations, I showed that small fixes to the Internet’s AS-level interconnections could drastically reduce the congestion in the network (PODC 2003). For example, I observed that adding parallel edges between adjacent ASes in proportion to the minimum of their degrees can ensure good Internet performance.

**Other Contributions**

Apart from my thesis research, I have conducted several studies on various networking topics such as the performance analysis of Internet protocols, transport layer approaches to improving the performance of TCP flows, and measurement studies of Internet infrastructure. One example is my work on selfish TCP congestion control (SIGCOMM 2002). For many years, the “socially responsible” congestion control behavior of Internet end-points was believed to be crucial for the stability of the network. To understand the impact of selfish end-point behavior, I performed a game-theoretic analysis of TCP’s congestion control mechanism. I showed that in traditional environments, where end-points employed early versions of TCP with Reno-style loss recovery and routers employed drop-tail buffering, selfish behavior has minimal impact on the network. However, recent advances in loss recovery (e.g., TCP SACK) and router buffering mechanisms (e.g., RED) have made the Internet more vulnerable to selfish behavior.

**Future Research Agenda**

**Toward a Robust and Efficient Internet.** An important observation in my thesis is that existing trends in the evolution and operation of the Internet could severely limit the future performance and robustness of the network. The current-day Internet is, in fact, already facing such a crisis. For example, in Japan, where a large number of homes employ very high-speed broadband Internet connections, the tera-bit national backbone has almost no spare capacity. Given this situation, it becomes crucial for both networking researchers...
as well as network operators to understand if, and how, we can make fundamental changes to the Internet that can guarantee robust and efficient functioning of the network as a whole.

To this end, in the future, I hope to identify good design points for the Internet topology—including ISP backbones, access networks and peering architectures—as well as for routing algorithms, both intra and inter-domain. These designs must be robust in the face of bandwidth upgrades, increasing node degrees in the backbone and access networks (due to advances in router design), and greater amounts of long-lived traffic (due to new applications like voice and video over IP). As an example, I discuss some thoughts on new designs for ISP backbones and intra-domain routing below.

National backbone carriers, such as AT&T and Sprint in the US, deploy backbone routers in large cities and towns, e.g., “football towns” across the US. Backbone routers are then physically linked in various different ways, such as by building a full mesh interconnection. A different interconnection scheme, that has several advantages compared to the current approaches, may be to link the routers using hierarchical, structured interconnection topologies. For example, routers in geographic sub-regions of the US, such as the north-east, may be interconnected as a hypercube. The low-dimensional hypercubes can, in turn, be interconnected to form a higher-dimensional national backbone topology. For the US, the dimension of the national backbone will be 4 or less, implying low node degrees, few backbone links and even fewer long-haul links. Such canonical backbone topologies offer several other advantages. Firstly, they can provide good end-to-end delays (due to the low diameter) without requiring a full interconnection among all backbone routers. Secondly, the topologies can provide robust and efficient performance (due to the high bisection bandwidth). Thirdly, the design of intra-domain routing is now vastly simplified: with a canonical backbone topology, routers will no longer have to explicitly discover backup paths on the basis of messages received from their neighbors, but can instead precompute and store the paths.

Of course, making the routing robust to arbitrary swings in user traffic, and designing appropriate schemes for peering and inter-domain traffic engineering are bigger challenges.

**Efficient Wireless Internet Access.** In the past few years, wireless networks have emerged as a dominant mechanism to access and share Internet connections. Today, wireless Access Points (APs) are deployed in a wide variety of scenarios—by individual home users, universities and enterprises, and competing businesses at malls and airports.

Recently, in collaboration with WiFiMaps.com, I conducted a study of the density and usage of wireless APs in urban areas. I found tens of APs deployed in close range of each other in several residential areas of Pittsburgh. Moreover, many of these APs used a fixed channel (channel 6) for transmission. The potential interference between APs in such naive, ad hoc urban deployments may result in poor utilization of the wireless medium, and slow, unreliable end-user Internet experience. With AP densities predicted to grow in the future, the problem of inefficient wireless access is likely to become even more pronounced over time.

In my future research, I hope to develop techniques for ensuring efficient wireless Internet access in such urban deployments. I intend to design specific solutions for individual deployment scenarios: For home environments, where little control can be exercised on the deployment of APs (such as how many are deployed, and at what locations), I will develop mechanisms that can be incorporated directly into the APs for automatic, dynamic channel selection, and transmit power control. Such mechanisms may have to employ prior knowledge of end-user Internet access patterns to provide the optimal performance. Solutions for deployments at airports, malls and shopping districts, on the other hand, must take into account the business concerns of the competing entities. Therefore, fairness across APs is at least as important a design goal as efficiency in wireless access. In university and enterprise scenarios, AP deployment is under the control of a central entity, and the primary goal is to ensure universal coverage. For such cases, I intend to develop generic guidelines for careful placement of the APs. Furthermore, I hope to invent distributed power control schemes which allow APs to extend coverage to remote areas of campuses, as well as to adapt to dynamic variations in the load on the network.