

Chapter 7

Conclusions

As researchers in networking, we are continuously trying to eliminate any bottlenecks in the Internet by proposing and evaluating alternative protocols, algorithms or techniques. Frequently, we simply consider the functions in the current router architecture (classification, route lookup, per-packet processing, buffering and scheduling) in isolation. This dissertation looks at the router as a whole and it asks the following question: Can the underlying technology (electronics in Silicon) keep up with the pace of traffic growth? Figure 1.3 shows that the answer is clearly no. In 10 years time, there will be a five-fold gap between information forwarding in electronics and the backbone traffic volume.

There are already several architectures [36, 92, 93] that try to overcome the limitations of electronics by using load balancing and massive parallelism. However, this thesis takes a different approach, and it explores what would happen if we used optical switching elements, which are known to scale to capacities that are unimaginable with electronics. Optics can, indeed, overcome the gap between traffic growth and switching capacity. However, we cannot use the traditional packet-switch design for optical switches because we (still) do not know how to buffer light in large amounts.

One switching technique that is not affected by this drawback of optics is circuit switching because circuit switching moves all contention away from the data path, and, thus, it eliminates the need for buffering in the forwarding path. But, it is worth asking: What is the price to pay to use this technique? How will the efficiency,

complexity and performance be affected? The first contribution of this thesis is a comparison of circuit and packet switching in the Internet, whether in electronics or optics. From analytical models, simulation and evidence from real networks, the conclusion is twofold:

- On one hand, circuit switching yields a very poor response time in access networks and LAN's with respect to packet switching. This is because of the blocking created by large file transfers when using circuits.
- On the other hand, in the core, circuit switching provides high reliability and scales better in capacity than packet switching without deteriorating the end-user response time or quality of service. The reason for this is that, first, circuit switches have a simpler data path and, second, the end-user response time is largely determined by the access links, which limits the maximum user-flow rate.

If we look at the backbone today, there is a lot of circuit switching in the form of SONET/SDH and DWDM switches. This thesis sustains that rather than disappear, these circuit switches will play a more relevant role in the future Internet. Currently, these core circuit switches are not integrated with the rest of the Internet, and IP treats the circuits as mere fixed-bandwidth, layer-2 paths between edge routers. In addition, these circuit switches are manually provisioned, and so it takes hours and even days to reconfigure them. They do react very slowly, and so they are vastly overprovisioned to account for any unexpected changes (for example, SONET/SDH provisions a parallel and disjoint path in a ring to accommodate for any sudden failure in the network). We would be better off if we had a circuit-switched system that reacts to the current network conditions in real-time.

The second contribution of this dissertation are two evolutionary approaches that integrate a circuit-switched core with the rest of an Internet that uses packet switching. The first approach (called TCP Switching) maps user flows to fine-grain, lightweight circuits in the core. The second approach monitors user flows to estimate the right size of the coarse-grain, heavyweight circuits that interconnect boundary

routers around the core. This thesis uses user flows extensively to control the circuit switches in the backbone. The amount of per-flow state these techniques require is quite manageable with current technology, and it does not limit the performance of the switch.

A word of caution: The introduction of any dynamic algorithm for circuit management may be slow. Many carriers are reluctant to fully automate the provisioning of their backbone and to let some edge routers (potentially belonging to their clients) make decisions involving millions of dollars. These carriers would prefer to start with an automatic network management software that gives recommendations to network operators, who in turn use a point-and-click interface to rapidly reconfigure the network. Only when carriers feel confident enough with the decision-making algorithms will they let these algorithms run the network. I believe this last step is inevitable because, as networks grow and become more complex, it will be increasingly more difficult for human operators to react fast enough to changes in the network.

This thesis proposes only two of many possible ways of scaling the backbone to accommodate the growth of Internet traffic. Other related techniques that also use circuit switching in the core are the proposals by Veeraraghavan et al., GMPLS, ASTN/ASON, ODSI and OIF. A different set of techniques are Optical Burst Switching and Optical Packet Switching. They introduce optical switches in the backbone that perform packet switching of either large bursts of data or regular IP packets. OBS and OPS represent a big departure from the switching techniques that operators of the large transport networks currently use for the core (SONET/SDH and DWDM). It will not be easy for OBS/OPS to convince operators to adopt their network model, especially since these two approaches will not improve the performance seen by the end user, as discussed in Chapter 2.¹

¹It is interesting to note that despite the almost simultaneous coming of age of IP and SONET/SDH in the late 80's, current IP routers have not been able to displace electronic circuit switching in the core, as shown in Table 2.1. This could be an indication of what can happen with OBS/OPS.

7.1 Future directions

One important aspect of circuit switching that has not been addressed in this thesis is the routing of circuits in the backbone. Routing has important implications in the performance and scalability of a circuit-switched network. For example, a network can increase its throughput without increasing the total capacity if the traffic load is balanced across multiple parallel paths. Even if the set of routes is not optimal, the throughput can be much higher than the trivial shortest-path-first solution. Routing decisions need to be fast so as to be reactive to changes in the network traffic. Routing also performs an important role in the robustness of the network because in case of a failure, the routing mechanism has to restore the broken paths as soon as possible. One can speed up recovery if a disjoint backup path has been pre-computed and perhaps even pre-provisioned before any failure occurs.

Finally, the analysis of circuit and packet switching can have many other applications; especially, when comparing preemptive and non-preemptive systems with several parallel channels or servers. A short list of applications include:

- Router and switch crossconnects with few or no buffers. These crossconnects resemble a bufferless optical network where most or all buffers are at the ingress and egress points. The approaches that have been presented in this thesis could be applicable in this situation.
- Wireless access networks, in which orthogonal channels are used to increase the capacity of the access network.
- HTTP 1.1, where a client pipelines its requests through several parallel connections to a proxy server.
- Computer clusters, in which workloads are so large that it becomes very expensive to switch contexts, and so tasks need to be executed to completion.

7.2 Final words

Hopefully, the ideas in this dissertation will serve as a useful foundation for the design and architecture of future networks, and they will encourage further research on the integration of circuit and packet switching. This approach will allow us to use all-optical switches that scale and can cope with the rapid growth of Internet traffic.