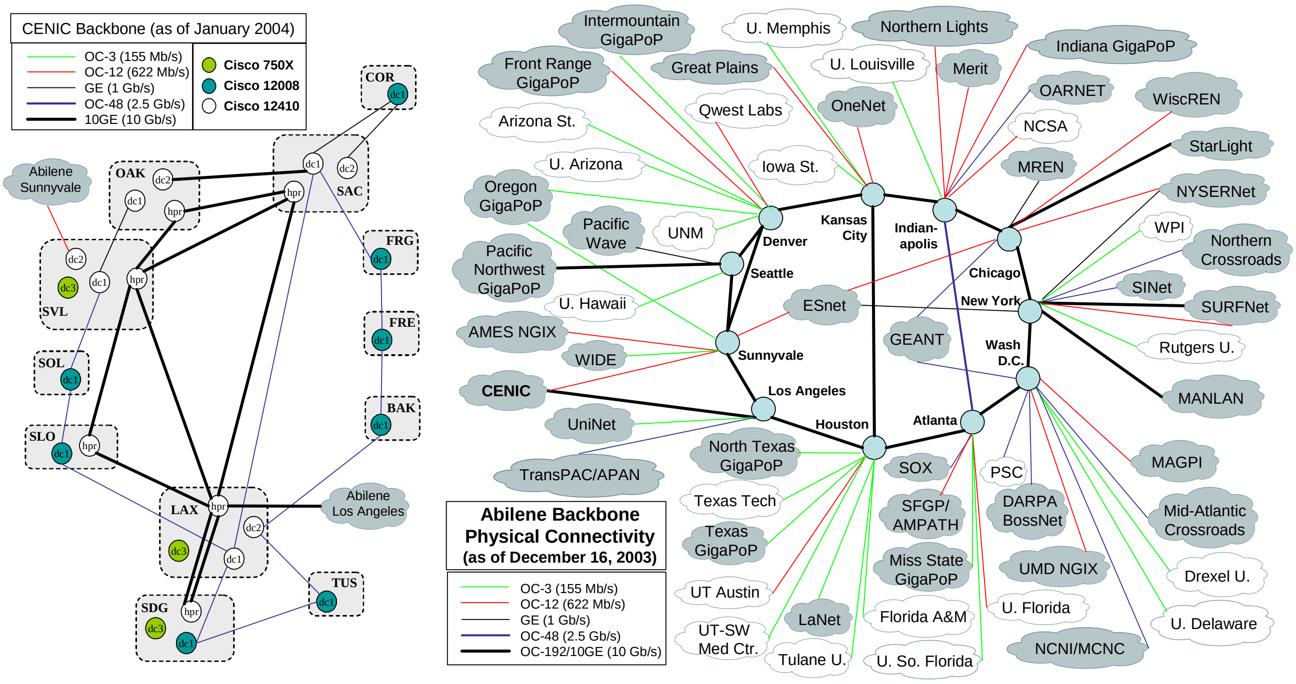

Figure 4: CENIC and Abilene networks. (Left): CENIC backbone. The CENIC backbone is comprised of two backbone networks in parallel—a high performance (HPR) network supporting the University of California system and other universities, and the digital California (DC) network supporting K-12 educational initiatives and local governments. Connectivity within each POP is provided by Layer-2 technologies, and connectivity to the network edge is not shown. (Right): Abilene network. Each node represents a router, and each link represents a physical connection between Abilene and another network. End user networks are represented in white, while peer networks (other backbones and exchange points) are represented in gray. Each router has only a few high bandwidth connections, however each physical connection can support many virtual connections that give the appearance of greater connectivity to higher levels of the Internet protocol stack. ESnet and GEANT are other backbone networks.

ample, nearly half of all users of the Internet in North America still have dial-up connections (generally 56kbps), only about 20% have broadband access (256kbps-6Mbps), and there is only a small number of users with large (10Gbps) bandwidth requirements [5]. Again, the cost effective handling of such diverse end user traffic requires that aggregation take place as close to the edge as possible and is explicitly supported by a common feature that these edge technologies have, namely a special ability to support high connectivity in order to aggregate end user traffic before sending it towards the core. Based on variability in population density, it is not only plausible but somewhat expected that there exist a wide variability in the network node connectivity.

Thus, a closer look at the technological and economic design issues in the network core and at the network edge provides a consistent story with regard to the forces (e.g., market demands, link costs, and equipment constraints) that appear to govern the build-out and provisioning of the ISPs' core networks. The tradeoffs that an ISP has to make between what is technologically feasible versus economically sensible can be expected to yield router-level connectivity maps where individual link capacities tend to increase while the degree of connectivity tends to decrease as one moves from the network edge to its core. To a first approximation, core routers tend to be fast (have high capacity), but have only a few high-speed connections; and edge routers are typically slower overall, but have many low-speed connections. Put differently, long-haul links within the core tend to be relatively few in numbers but their capacity is typically high.

3.3 Heuristically Optimal Networks

The simple technological and economic considerations listed above suggest that a reasonably "good" design for a single ISP's network is one in which the core is constructed as a loose mesh of high speed, low connectivity routers which carry heavily aggregated traffic over high bandwidth links. Accordingly, this mesh-like core is supported by a hierarchical tree-like structure at the edges whose purpose is to aggregate traffic through high connectivity. We will refer to this design as *heuristically optimal* to reflect its consistency with real design considerations.

As evidence that this heuristic design shares similar qualitative features with the real Internet, we consider the real router-level connectivity of the Internet as it exists for the educational networks of Abilene and CENIC (Figure 4). The Abilene Network is the Internet backbone network for higher education, and it is part of the Internet2 initiative [1]. It is comprised of high-speed connections between core routers located in 11 U.S. cities and carries approximately 1% of all traffic in North America[5]. The Abilene backbone is a sparsely connected mesh, with connectivity to regional and local customers provided by some minimal amount of redundancy. Abilene is built using Juniper T640 routers, which are configured to have anywhere from five connections (in Los Angeles) to twelve connections (in New York). Abilene maintains peering connections

[5]Of the approximate 80,000 - 140,000 terabytes per month of traffic in 2002 [35], Abilene carried approximately 11,000 terabytes of total traffic for the year [27]. Here, "carried" traffic refers to traffic that traversed an Abilene router. Since Abilene does not peer with commercial ISPs, packets that traverse an Abilene router are unlikely to have traversed any portion of the commercial Internet.