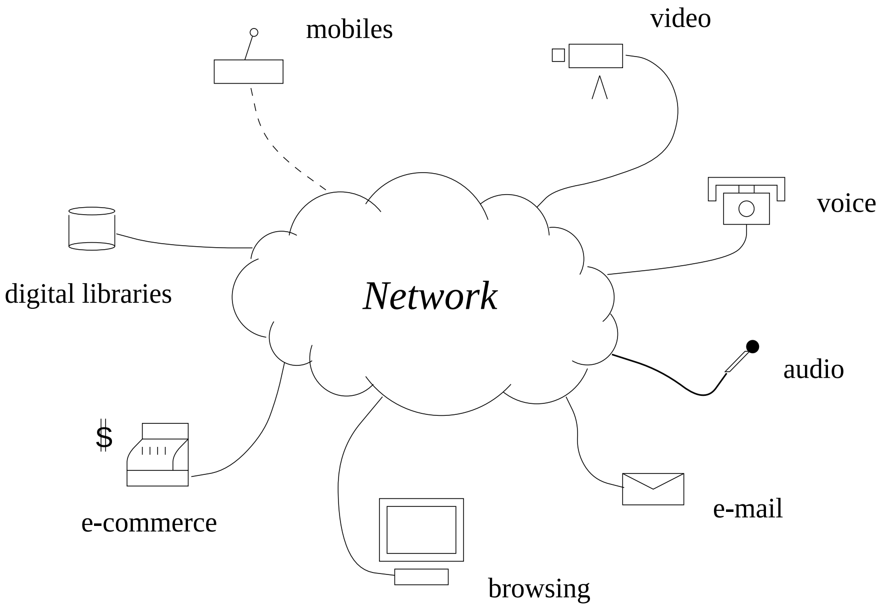
Introduction

Components of Modern Network Environment



- applications with diverse QoS requirements
- shared network
- end system/host (shared)

Components:

- applications
- network
- end system

$\longrightarrow$ composed of software & hardware

Hardware Components:

- routers/switches
- transmission media (e.g., fiber optic)
- end systems (e.g., workstation, laptop)
- other special purpose devices (e.g., capture, display, compression)

Software Components:

- network protocols (routers & end systems)
- operating systems (end systems & routers)
- special purpose device drivers (capture/display/compression)
- application software
- middleware (least well-defined)

Wetware Component:

Homo sapiens; through HCI, ultimate driver of application (e.g., Web)

Organizational Component:

- economic component (e.g., pricing, e-commerce)
- political component (e.g., regulation, policy routing)

$\longrightarrow$ collectively determine behavior of system

Overall Objective:

- *Design/Control.* Facilitate QoS-sensitive sharing of resources w.r.t. implicitly/explicitly specified criteria
- *Physics.* Understand behavior of given system (e.g., current Internet)

$\longrightarrow$ advancement/interplay on both fronts

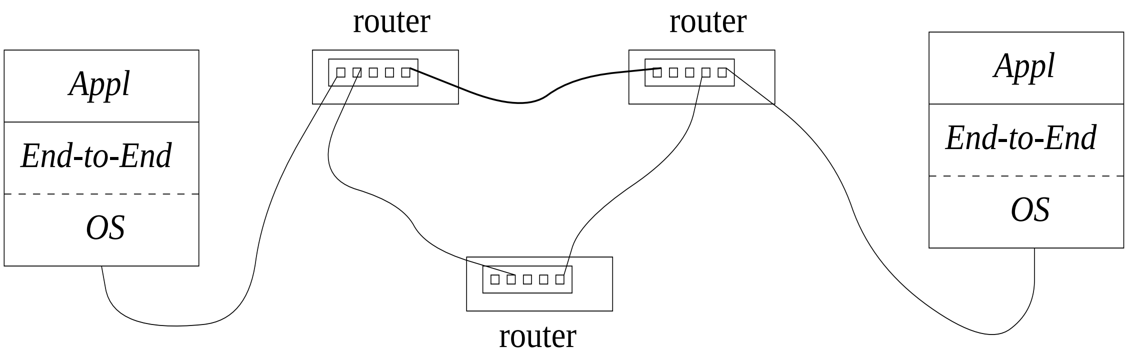
Ex.: IETF Int-Serv, Diff-Serv for next generation IP networks (i.e., Internet), some activity on ATM Forum; traffic and workload characterization, global network dynamics

Our Focus:

Network control.

Spans:

- network proper (i.e., routers/network layer)
- end-to-end control (i.e., end system/transport layer)
- end system scheduling (i.e., CPU/OS)
- application layer control



Challenges

Technological:

- broadband wide area networks

  $\longrightarrow$ delay-bandwidth product problem

- scale w.r.t. system size

  $\longrightarrow$ per-flow vs. aggregate-flow control

- diverse QoS requirements

  $\longrightarrow$ multimedia

- integrated services

  $\longrightarrow$ telephony & data on common network

- hybrid wireline/wireless system

  $\longrightarrow$ noise, mobility, resource limitations

- heterogeneous networks and backward compatibility

  $\longrightarrow$ IPv4/v6, ATM, IP-over-ATM, IP-over-SONET

- integration with other systems

  $\longrightarrow$ DB/multimedia representation, security, etc.

Other:

- part of economic system

  $\longrightarrow$ pricing, accounting, transactions, middleware

- political, etc.

  $\longrightarrow$ FCC regulations, standards bodies

Core Architectural Properties:

- scalability
- multiservice
- fairness
- implementability
- integration
- security
- reliability

Scalability:

$\longrightarrow$ w.r.t. number of users & devices

- aggregate-flow control (vs. per-flow control)
  - zero per-flow state
  - programmable state (soft state)
  - packet scheduler
  - packet classifier (part of scheduler)
- end-to-end vs. per-hop control
  - push complexity to the edge (biased trade-off)

    $\longrightarrow$ traditional Internet control paradigm
  - per-flow control at edge & aggregate-flow control at router
  - complementary (cooperation)

- scalable admission control
  - measurement-based
  - pricing (at entry point)
  - lightweight signalling, state monitoring
- efficiency
  - simple algorithms
  - low time, space, communication complexity algorithms
  - low signalling overhead
- robustness
  - decentralized control
  - minimal system state
  - fault containment
  - fast recovery from component failure

Multiservice:

$\longrightarrow$ spectrum of user-adaptive services

- guaranteed service (GS)
  - QoS guarantees (deterministic & statistical)
  - resource reservation (per-flow)
  - admission control
  - achieves perfect protection
  - scalable only if no. of GS users is small, or information sharing (broadcast, multicast)
- non-guaranteed service
  - graded but non-stringent QoS
  - elastic, stratified best-effort, differentiated service
  - weaker protection
  - relaxation of GS control features
  - for scalability

- user adaptation
  - user/network contract (admission control)
  - dynamic user control
  - efficient QoS allocation
- other service dimensions
  - security services
  - accounting service
  - middleware services (e.g., name, proxy selection)

Fairness:

$\longrightarrow$ "who gets what and how much" problem

- equal share (max-min)
  - best-effort service class (e.g., Internet)
  - QoS is secondary/tertiary objective
  - nontrivial to achieve (e.g., function of control loop)
  - cooperative (specific congestion controls, router)
  - only minimally realized on Internet
- competitive (laisser faire)
  - purely behavioral
  - "you get what you can get"
  - absence of normative, imposed criteria
  - noncooperative
  - intrinsic to today's Internet

- engineered competitiveness
  - further behavioral constraints/rules (e.g., packet scheduling, pricing)
  - system objective: noncooperative competitiveness leads to desirable QoS provisioning
  - stability
  - efficiency (w.r.t. network resource allocation)
  - user needs (utility function)
- cooperative competitiveness
  - long-term resource allocation (e.g., leasing)
  - ISP cooperation (e.g., pricing, partnerships)
  - service bundling (intermediaries)

Implementability:

- feasible algorithms
  - simple, fast, space/communication efficient
  - “good” algorithms (not necessarily optimal)
- compatibility with existing networks and technology
  - IP Internet (IPv4, IPv6, TCP, etc.)
  - ATM, mobile IP, IPsec
  - backward compatibility & transparency
  - packet switching technology (i.e., router)
  - transmission media (broadband, wireless)
  - end-to-end, per-hop
  - amount of change required

Integration:

- with other system control components
  - OS (i.e., CPU) scheduling
  - application layer control (e.g., compression)
- with high-level services
  - security (both high and low)
  - middleware
  - DB, information representation, user interfaces
  - economic subsystem