Network Layer Overview

Kai Shen

Internet Architecture

Bottom-up:
- **physical**: electromagnetic signals “on the wire”
- **link**: data transfer between neighboring network elements
  - encoding, framing, error correction, access control for shared links
- **network**: host-to-host connectivity
  - routing, addressing
- **transport**: host-host data transport
  - reliable data transport, congestion control, flow control
- **application**: anything you want to do on computer networks

Network Layer Function

- transport packet from sending to receiving hosts
  - **routing**: determine a path from source to dest and route packets along the path
  - **addressing**: uniquely identify each node in the network
- network connecting devices
  - called “routers”
  - participate in network protocols
- links
  - connect adjacent hosts, routers

Protocol Layers and Data Flows
Data Formation Across Layers

Each layer takes data from above
- adds header information to create new data unit
- passes new data unit to layer below

Network Service Model

- loss-free delivery?
- in-order delivery?
- preservation of inter-packet delay (no jitter)?
- guaranteed bandwidth?
- congestion feedback to sender?

Connection-based Networks

- guaranteed bandwidth, jitter-free, in-order delivery build on the concept of connections, or virtual circuits
- require signaling protocols to setup, maintain, and teardown virtual circuit
- router maintains state about ongoing connections

Packet Switching

- no connection ⇔ every packet is on its own
- stateless routers ⇔ no need to remember anything about packets
- packets forwarded independently from each other
  - packets between same source-dest pair may take different paths
Packet Switching vs. Connection-based Networks

Packet switching
- poor service guarantee
- "elastic" service
- efficiency
- scalability
- robustness
- flexibility/customization
  - simple network core, complexity at "edge"
  - manage, control, adapt at "smart" end systems (computers)

Connection-based
- evolved from telephony
- guaranteed service
  - e.g., human conversation:
    - strict timing, reliability requirements
- hard to evolve
- complex network core

Internet employs packet switching; connection-based are more suitable for networks with "dumb" end terminals - telephones.

Routing Principles

Routing protocol
Goal: determine "good" path (sequence of routers) thru network from source to dest.

Graph abstraction for routing algorithms:
- graph nodes are hosts or routers
- graph edges are links
  - link cost: delay, $ cost, or congestion level

“good” path:
- typically means minimum cost path

Routing Algorithm Classification

Global information:
- all routers have complete topology, link cost info
- “link state” algorithm

Decentralized:
- router knows connected neighbors, link costs to neighbors
- exchange of info with neighbors to learn remote parts of the network, may take many learning rounds
- “distance vector” algorithm

A Link-State Routing Algorithm

Dijkstra’s algorithm
- Network topology, link costs/distances known to all nodes
  - accomplished via “link state broadcast”
  - all nodes have same info
- The algorithm calculates the shortest paths from one specific node ("source") to all other nodes
  - Basic approach: gradually expands a set “N”, containing nodes whose shortest paths from the source are known
    - initially “N” contains only the source itself
    - at every step one more node’s shortest path from the source is learned, this node is then added to “N”
    - eventually “N” includes every node and the algorithm terminates
Dijkstra’s Algorithm (cont.)

"N", containing nodes with known shortest paths from source

Key step: How to expand "N" to include one more node?

- "1-hop paths":
  - paths from source to dest. v (not in N) whose last hop before v is in N
  - D(v) as the distance of the shortest 1-hop path to v

- For arbitrary v, is D(v) shortest path distance to v?
- For v* with shortest D(v) among all v's not in N, D(v*) is the shortest path distance to v*.

Dijkstra’s Algorithm: An Example

N: set of nodes whose shortest paths are currently known

D(v): distance for shortest 1-hop path from source to dest. v

p(v): predecessor node along path from source to dest. v

Step | N  | D(B),p(B) | D(C),p(C) | D(D),p(D) | D(E),p(E) | D(F),p(F) |
-----|-----|-----------|-----------|-----------|-----------|-----------|
 0   | A   | 2,A       | 5,A       | 1,A       | infinity  | infinity  |
 1   | AD  | 2,A       | 4,D       | 1,A       | 2,D       | infinity  |
 2   | ADE | 2,A       | 3,E       | 2,D       | 4,E       | 4,E       |
 3   | ADEB| 3,E       | 4,E       | 4,E       |           |           |
 4   | ADEBC|    |           |           |           |           |
 5   | ADEBCF|          |           |           |           |           |

Dijkstra’s Algorithm: Complexity

Algorithm complexity: n nodes, e links

- Each iteration: need to check all nodes, v, not in N
  \( n^2 \) checks: \( O(n^2) \)
- Update 1-hop paths: \( O(e) \)
- Total: \( O(n^2+e) \), or \( O(n^2) \)
- Using Fibonacci heap to find minimum distance node
  \( O(n \log n + e) \)

Dijkstra’s Algorithm: Stability

Oscillations possible:

- e.g., link cost = amount of carried traffic

Solutions:

- asynchronous (at different time) adjustments across routers
- stable cost metric (independent of routing policy)
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