Network Layer Overview

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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-to-host data transport
  - reliable data transport, congestion control, flow control
- application: anything you want to do on computer networks

Fundamental Network Layer Function

- fundamental function: transport packet from sending to receiving hosts
  - addressing: uniquely identify each node in the network
  - routing: determine a path from source to dest and route packets along the path
- network layer protocols in every host, router

Protocol Layering and Data

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

source
- application
- transport
- network
- link
- physical

destination
- application
- transport
- network
- link
- physical

message segment packet frame
Data Flow across Layers

Application → Transport → Network → Link → Physical

Network Service Model

Q: What service model is needed in transporting packets from sender to receiver?
- guaranteed bandwidth?
- preservation of inter-packet delay (no jitter)?
- loss-free delivery?
- in-order delivery?
- congestion feedback to sender?

"Analogy"
Q: What service model is needed in air travel (transporting people from location to location)?
- on-time arrival?
- no lost baggage?
- may get bumped out of flights due to overbooking?

Virtual Circuits
- provide services such as guaranteed bandwidth, jitter-free, in-order delivery, ...
- require signaling protocols to setup, maintain, and teardown virtual circuit
- router maintains state about ongoing connections

Packet Switching
- no call setup at network layer
- routers: no state about end-to-end connections
- packets forwarded independently from each other
- packets between some source-dest pair may take different paths
Packet Switching vs. Virtual Circuits

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

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

Internet employs packet switching; virtual circuits are used 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 physical 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 physically-connected neighbors, link costs to neighbors
- exchange of info with neighbors, may take many rounds to converge
- "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.)

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

- For each v not in N
  - currently known paths are paths from source to v whose intermediaries are all in N
  - D(v) as the distance of current known shortest path
- For a node with shortest D(v) among all v's not in N, its currently known shortest path is its globally shortest path

A is the source. N currently contains A, D, E.

Dijkstra's Algorithm: An Example

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 | infinity | infinity | infinity |
1 | AD | 2, A | 4, D | 1, A | infinity | infinity |
2 | ADE | 2, A | 3, E | 2, D | 4, E | 4, E |
3 | ADEB | 3, E | 4, E | 4, E | 4, E | 4, E |
4 | ADEBC | 4, E | 4, E | 4, E | 4, E | 4, E |
5 | ADEBCF | 4, E | 4, E | 4, E | 4, E | 4, E |

Dijkstra's Algorithm: Discussion

- Algorithm complexity: n nodes
- each iteration: need to check all nodes, w, not in N
- \( n(n-1)/2 \) comparisons: O(n^2)
- using Fibonacci heap to find minimum distance node: O(n log n + e)

Oscillations possible:
- e.g., link cost = amount of carried traffic
- solution: stable cost metric; asynchronous (random-time) link cost collection

Network Routing

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

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

Decentralized:
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- routers exchange of info with neighbors
Distance Vector Routing

- **Routing table**: (at each host) the next hop for each destination in the network
- **Distance vector routing**: the routing table is constructed from a distance vector at each node
- Distance vectors can be maintained in a decentralized fashion

Distance Vector: An Example

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>D (E,x,y) via first hop x</td>
<td>1</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>D (E,D,A)</td>
<td>8</td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>D (E,B,A)</td>
<td>8</td>
<td>11</td>
<td>4</td>
</tr>
</tbody>
</table>

Distance vector at node E

<table>
<thead>
<tr>
<th>Destination</th>
<th>A</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>D (E,D,C) = c(E,D) + shortest(D,C)</td>
<td>2+2 = 4</td>
<td></td>
</tr>
<tr>
<td>D (E,D,A) = c(E,D) + shortest(D,A)</td>
<td>2+3 = 5</td>
<td><strong>Loop!</strong></td>
</tr>
<tr>
<td>D (E,B,A) = c(E,B) + shortest(B,A)</td>
<td>8+6 = 14</td>
<td><strong>Loop!</strong></td>
</tr>
</tbody>
</table>

Distance Vector to Routing Table

<table>
<thead>
<tr>
<th>Destination</th>
<th>A</th>
<th>B</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost to destination via</td>
<td>14</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>1</td>
<td>D,4</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>7</td>
<td>D,5</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>6</td>
<td>D,4</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>4</td>
<td>D,4</td>
<td></td>
</tr>
</tbody>
</table>

Distance vector Routing Table

Disclaimer

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