Routing in Switched Networks

Chapter 19 in Stallings 10th Edition

Routing in Packet Switching Networks

- Key design issue for (packet) switched networks
- Select route across network between end nodes
- Characteristics required:
  - —Correctness
  - —Simplicity
  - —Robustness
  - —Stability
  - —Fairness
  - —Optimality
  - —Efficiency

Routing in Circuit Switched Network

- Many connections will need paths through more than one switch
- Need to find a route
  - —Efficiency
  - —Resilience
- Public telephone switches are a tree structure
  - —Static routing uses the same approach all the time
- Dynamic routing allows for changes in routing depending on traffic
  - —Uses a peer structure for nodes

Elements of Routing Techniques for Packet-Switching Networks

Table 19.1

Performance Criteria Number of hops Cost Delay Throughput **Decision Time** Packet (datagram) Session (virtual circuit) **Decision Place** Each node (distributed) Central node (centralized) Originating node (source)	**Network Information Source** None Local Adjacent node Nodes along route All nodes **Network Information Update Timing** Continuous Periodic Major load change Topology change

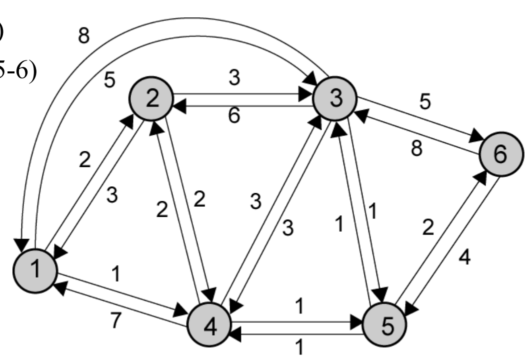
Performance Criteria

- Used for selection of route
  - —Minimum hop
  - —Least cost
  - —Delay
  - —Throughput

- Simplest is to choose "minimum hop"
- Can be generalized as "least cost" routing
- "least cost" is more flexible and is more common than "minimum hop"

Example Packet Switched Network

- ◆Example
  - –communicating nodes: node-1 to node-6
  - –what is of interest?
    - »Shortest path (1-3-6)
    - »least cost path (1-4-5-6)



Decision Time and Place

- Time
  - —Packet or virtual circuit basis
- Place
  - —Distributed
    - Made by each node
  - —Centralized
    - requires central node
  - —Source
    - originating node

Network Information Source and Update Timing

- Routing decisions usually based on knowledge of network
  - — (not always)
- Distributed routing
  - — Nodes use local knowledge
  - — May collect info from adjacent nodes
  - — May collect info from all nodes on a potential route
- Central routing
  - — Collect info from all nodes
- Update timing
  - — When is network info held by nodes updated?
    - Fixed - never updated
    - Adaptive - regular updates
    - Continuous
    - Periodic
    - Major load change
    - Topology change

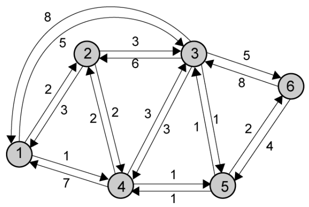
Routing Strategies

- We will discuss several strategies:
  - —Fixed Routing
  - —Flooding Routing
  - —Random Routing
  - —Adaptive Routing

Routing Strategies - Fixed Routing

- Use a single permanent route for each source to destination pair of nodes
- Determined using a least cost algorithm
- Route is fixed
  - —Until a change in network topology
  - —Based on expected traffic or capacity
- Advantage is simplicity
- Disadvantage is lack of flexibility
  - —Does not react to network failure or congestion

Fixed Routing Tables



CENTRAL ROUTING DIRECTORY

	From Node					
To Node	1	2	3	4	5	6
1	—	1	5	2	4	5
2	2	—	5	2	4	5
3	4	3	—	5	3	5
4	4	4	5	—	4	5
5	4	4	5	5	—	5
6	4	4	5	5	6	—

Node 1 Directory

Destination	Next Node
2	2
3	4
4	4
5	4
6	4

Node 2 Directory

Destination	Next Node
1	1
3	3
4	4
5	4
6	4

Node 3 Directory

Destination	Next Node
1	5
2	5
4	5
5	5
6	5

Node 4 Directory

Destination	Next Node
1	2
2	2
3	5
5	5
6	5

Node 5 Directory

Destination	Next Node
1	4
2	4
3	3
4	4
6	6

Node 6 Directory

Destination	Next Node
1	5
2	5
3	5
4	5
5	5

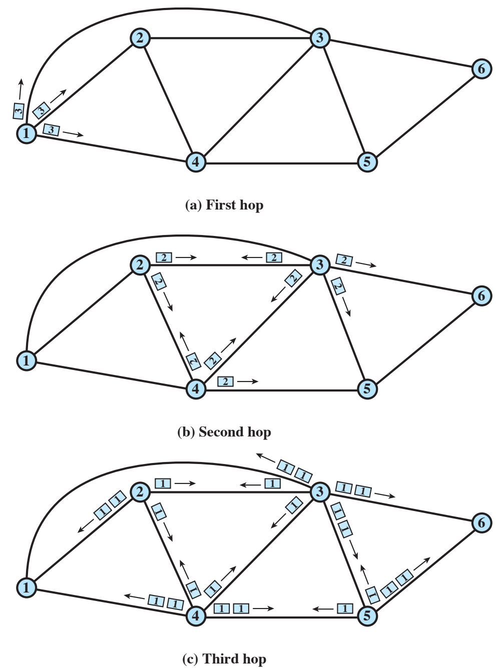
Routing Strategies - Flooding

- Packet sent by node to every neighbor
- Eventually multiple copies arrive at destination
- No network information required
- Each packet is uniquely numbered so duplicates can be discarded
- Need to limit incessant retransmission of packets
  - —Nodes can remember identity of packets retransmitted
  - —Can include a hop count in packets

Flooding Example

Figure 19.3

Assigned Hop Count is 3



Properties of Flooding

- **All possible routes are tried** → Highly robust → Can be used to send emergency messages
- **At least one packet will have taken minimum hop route**
- **Nodes directly or indirectly connected to source are visited**
- **Disadvantages:** → High traffic load generated → Security concerns

Random Routing

- Node selects one outgoing path for retransmission of incoming packet
- Selection can be random or round robin
  - Can select outgoing path based on probability calculation, i.e.
    - P_i probability of selecting link *i*
    - R_i data rate of link *i*
    - Sum is taken over all outgoing candidate links

$$P_i = \frac{R_i}{\sum_j R_j}$$

- No network info needed
- Route is typically not least cost nor minimum hop

Routing Strategies - Adaptive Routing

- Used by almost all packet switching networks
- Routing decisions change as conditions on the network change due to failure or congestion
- Requires information about network

Disadvantages:	Decisions more complex
	Tradeoff between quality of network information and overhead
	Reacting too quickly can cause oscillation
	Reacting too slowly means information may be irrelevant

Classification of Adaptive Routing Strategies

- A convenient way to classify is on the basis of information source

Local (isolated)
- Route to outgoing link with shortest queue
- Can include bias for each destination
- Rarely used - does not make use of available information

Adjacent nodes
- Takes advantage of delay and outage information
- Distributed or centralized

All nodes
- Like adjacent

Node 4's Bias Table for Destination 6

Next Node	Bias
1	9
2	6
3	3
5	0

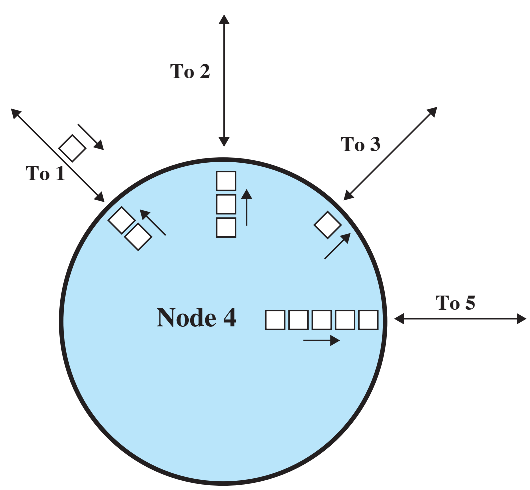
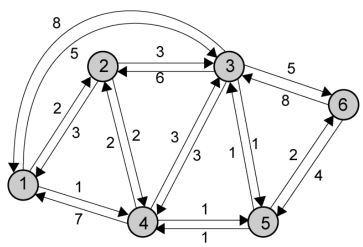


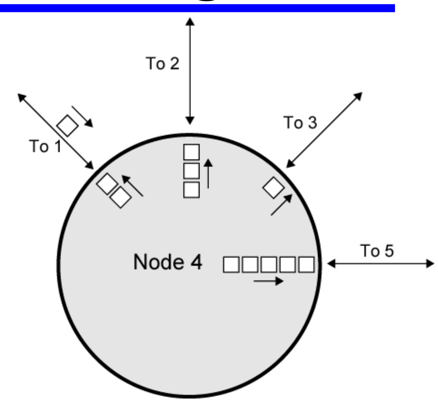
Figure 19.4 Example of Isolated Adaptive Routing

Isolated Adaptive Routing

Node 4's Bias Table for Destination 6

Next Node	Bias
1	9
2	6
3	3
5	0





Algorithm:
minimize $Q + B_i$
where
Q is queue length
B_i is bias for destination i

ARPANET Routing Strategies 1st Generation

Distance Vector Routing

- **1969**
- Distributed adaptive using estimated delay
  - —Queue length used as estimate of delay
- Version of Bellman-Ford algorithm
- Node exchanges delay vector with neighbors
- Update routing table based on incoming information
- Doesn't consider line speed, just queue length and responds slowly to congestion

Destination	Delay	Next node
1	0	—
2	2	2
3	5	3
4	1	4
5	6	3
6	8	3

D_1 (Delay), S_1 (Next node)

(a) Node 1's Routing table before update

D_2	D_3	D_4
3	7	5
0	4	2
3	0	2
2	2	0
3	1	1
5	3	3

(b) Delay vectors sent to node 1 from neighbor nodes

Destination	Delay	Next node
1	0	—
2	2	2
3	3	4
4	1	4
5	2	4
6	4	4

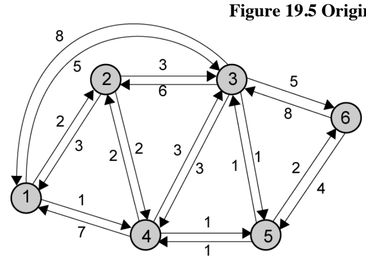
$l_{1,2} = 2$

$l_{1,3} = 5$

$l_{1,4} = 1$

(c) Node 1's routing table after update and link costs used in update

Figure 19.5 Original ARPANET Routing Algorithm



ARPANET Routing Strategies 2nd Generation

Link-State Routing

- **1979**
- Distributed adaptive using delay criterion
  - —Using timestamps of arrival, departure and ACK times
- Re-computes average delays every 10 seconds
- Any changes are flooded to all other nodes
- Re-computes routing using Dijkstra's algorithm
- Good under light and medium loads
- Under heavy loads, little correlation between reported delays and those experienced

ARPANET Routing Strategies (3)

- Third Generation (1987)
  - —Link cost calculations changed
  - —Measure average delay over last 10 seconds
  - —Normalize based on current value and previous results

Least Cost Algorithms

- Basis for routing decisions
  - —Can minimize hop by setting each link cost to unity
  - —Can have link value inversely proportional to capacity
- Given network graph
  - —Nodes connected by bi-directional links
  - —Each link has a cost in each direction
- Define cost of path between two nodes as sum of costs of links traversed
- For each pair of nodes, find a path with the least cost
- Link costs in different directions may be different
  - —E.g. length of packet queue

Dijkstra’s Algorithm Definitions

- Find shortest paths from given source to all other nodes, by developing paths in order of increasing path length
- **N** = set of nodes in the network
- s = source node
- **T** = set of nodes so far incorporated by the algorithm
- w(i, j) = link cost from node i to node j
  - w(i, i) = 0
  - w(i, j) = ∞ if the two nodes are not directly connected
  - w(i, j) $\geq$ 0 if the two nodes are directly connected
- L(n) = cost of least-cost path from node s to node n currently known
  - At termination, L(n) is cost of least-cost path from s to n

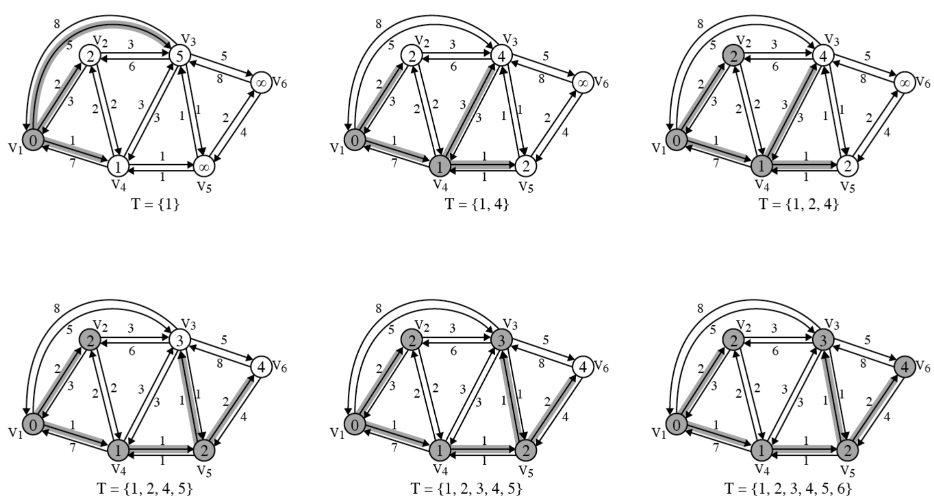
Dijkstra’s Algorithm Method

- Step 1 [Initialization]
  - **T** = {s} Set of nodes so far incorporated consists of only source node
  - L(n) = w(s, n) for n $\neq$ s
  - Initial path costs to neighboring nodes are simply link costs
- Step 2 [Get Next Node]
  - Find neighboring node *x* not in **T** with least-cost path from s
  - Incorporate node into **T**
- Step 3 [Update Least-Cost Paths]
  - L(n) = min[L(n), L(x) + w(x, n)] for all n $\notin$ T
  - If latter term is minimum, path from s to n is path from s to x concatenated with edge from x to n
- Algorithm terminates when all nodes have been added to T

Dijkstra's Algorithm Notes

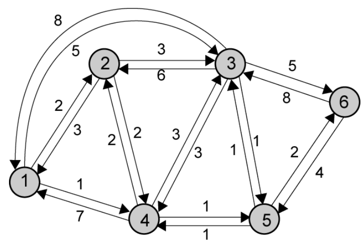
- At termination, value L(x) associated with each node x is cost (length) of least-cost path from s to x.
- In addition, T defines least-cost path from s to each other node
- One iteration of steps 2 and 3 adds one new node to T
  - —Defines least cost path from s to that node

Example of Dijkstra's Algorithm



Results of Example Dijkstra's Algorithm

Iteration	T	L(2)	Path	L(3)	Path	L(4)	Path	L(5)	Path	L(6)	Path
1	{1}	2	1 - 2	5	1 - 3	1	1 - 4	∞	—	∞	—
2	{1, 4}	2	1 - 2	4	1 - 4 - 3	1	1 - 4	2	1 - 4 - 5	∞	—
3	{1, 2, 4}	2	1 - 2	4	1 - 4 - 3	1	1 - 4	2	1 - 4 - 5	∞	—
4	{1, 2, 4, 5}	2	1 - 2	3	1 - 4 - 5 - 3	1	1 - 4	2	1 - 4 - 5	4	1 - 4 - 5 - 6
5	{1, 2, 3, 4, 5}	2	1 - 2	3	1 - 4 - 5 - 3	1	1 - 4	2	1 - 4 - 5	4	1 - 4 - 5 - 6
6	{1, 2, 3, 4, 5, 6}	2	1 - 2	3	1 - 4 - 5 - 3	1	1 - 4	2	1 - 4 - 5	4	1 - 4 - 5 - 6



Bellman-Ford Algorithm Definitions

- Essential idea
  - first, find shortest paths from given node subject to the constraint that the paths contain at most 1 link
  - next, find the shortest paths with a constraint of paths of at most 2 links
  - and so on
- Definitions
  - *s* = source node
  - w(i, j) = link cost from node i to node j
    - w(*i*, *i*) = 0
    - w(*i*, *j*) = ∞ if the two nodes are not directly connected
    - w(*i*, *j*) ≥ 0 if the two nodes are directly connected
  - *h* = maximum number of links in path at current stage of the algorithm
    - i.e. *h* = max length of a path currently considered
  - $L_h(n)$ = cost of least-cost path from *s* to n under constraint of no more than *h* links

Bellman-Ford Algorithm Method

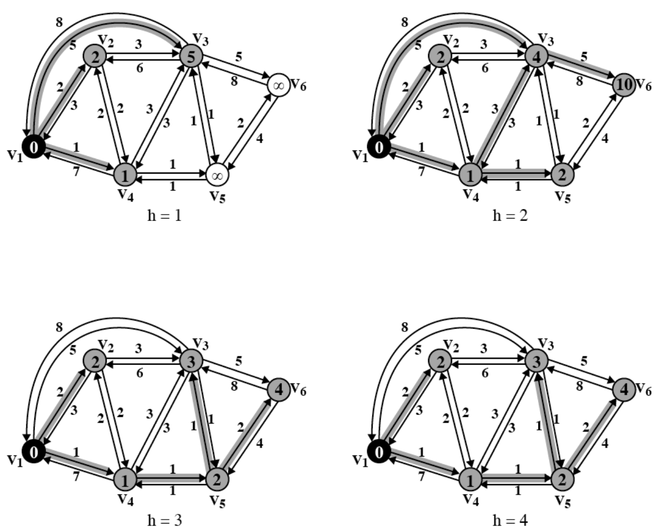
- Step 1 [Initialization]
  - $L_0(n) = \infty$, for all $n \neq s$
  - $L_h(s) = 0$, for all h

- Step 2 [Update]
  - For each successive $h \geq 0$
    - For each $n \neq s$, compute

$$L_{h+1}(n) = \min_j [L_h(j) + w(j,n)]$$

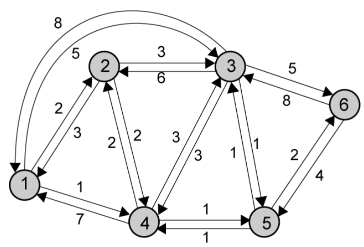
  - Connect n with predecessor node j that achieves minimum
  - Eliminate any connection of n with different predecessor node formed during an earlier iteration
  - Path from s to n terminates with link from j to n

Example of Bellman-Ford Algorithm



Results of Bellman-Ford Example

h	$L_h(2)$	Path	$L_h(3)$	Path	$L_h(4)$	Path	$L_h(5)$	Path	$L_h(6)$	Path
0	∞	—	∞	—	∞	—	∞	—	∞	—
1	2	1 - 2	5	1 - 3	1	1 - 4	∞	—	∞	—
2	2	1 - 2	4	1 - 4 - 3	1	1 - 4	2	1 - 4 - 5	10	1- 3 - 6
3	2	1 - 2	3	1 - 4 - 5 - 3	1	1 - 4	2	1 - 4 - 5	4	1 - 4 - 5 - 6
4	2	1 - 2	3	1 - 4 - 5 - 3	1	1 - 4	2	1 - 4 - 5	4	1 - 4 - 5 - 6

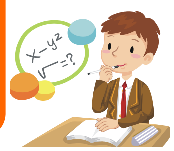


Comparison

- Bellman-Ford
  - Calculation for node n needs link cost to neighboring nodes plus total cost to each neighbor from s
  - Each node can maintain set of costs and paths for every other node
  - Can exchange information with direct neighbors
  - Can update costs and paths based on information from neighbors and knowledge of link costs
- Dijkstra
  - Each node needs complete topology
  - Must know link costs of all links in network
  - Must exchange information with all other nodes

Evaluation

Dependent on
- Processing time of algorithms
- Amount of information required from other nodes



Implementation specific

Both converge under static topology and costs

Both converge to same solution

If link costs change, algorithms attempt to catch up

If link costs depend on traffic, which depends on routes chosen, may have feedback instability

Summary

- Routing in packet-switching networks
  - —Characteristics
  - —Routing strategies
- Examples: Routing in ARPANET
  - —First generation: Distance Vector Routing
  - —Second generation: Link-State Routing
  - —Third generation
- Internet routing protocols
  - —Autonomous systems
  - —Approaches to routing
  - —Border gateway protocol
  - —OSPF protocol
- Least-cost algorithms
  - —Dijkstra's algorithm
  - —Bellman-Ford algorithm
  - —Comparison