DATA AND COMPUTER COMMUNICATIONS

Lecture 4 Wide Area Networks - Routing

Mei Yang

Based on Lecture slides by William Stallings

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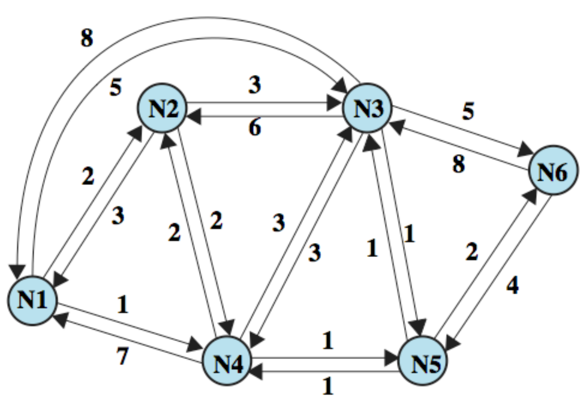
Routing in Packet Switched Network

- key design issue for (packet) switched networks
- select route across network between end nodes
- characteristics required:
  - correctness
  - simplicity
  - robustness
  - stability
  - fairness
  - optimality
  - efficiency

Performance Criteria

- used for selection of route
- simplest is "minimum hop"
- can be generalized as "least cost"
- because "least cost" is more flexible it is more common than "minimum hop"

Example of Packet Switched Network



Decision Time and Place

decision time

- packet or virtual circuit basis
- fixed or dynamically changing

decision place

- distributed - made by each node
  - more complex, but more robust
- centralized – made by a designated node
- source – made by source station

Network Information Source and Update Timing

- routing decisions usually based on knowledge of network, traffic load, and link cost
  - distributed routing
    - using local knowledge, information from adjacent nodes, information from all nodes on a potential route
  - central routing

issue of update timing

- depends on routing strategy
- fixed - never updated
- adaptive - regular updates

Routing Strategies - Fixed Routing

- use a single permanent route for each source to destination pair
- determined using a least cost algorithm
- route is fixed
  - at least until a change in network topology
  - hence cannot respond to traffic changes
- advantage is simplicity
- disadvantage is lack of flexibility

Fixed Routing Tables

CENTRAL ROUTING DIRECTORY

To Node \ From 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

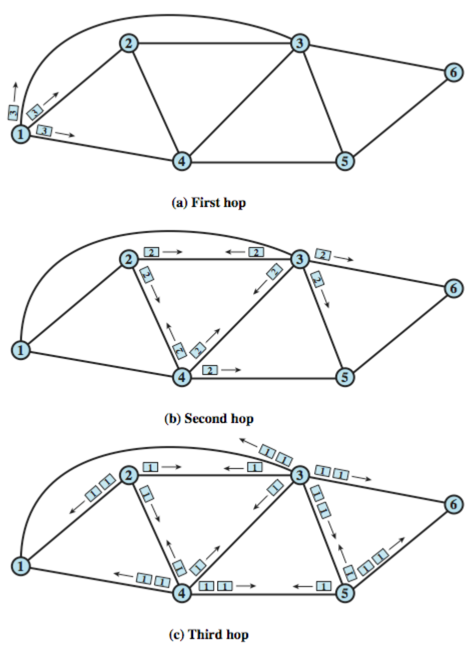
Node 6 Directory

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

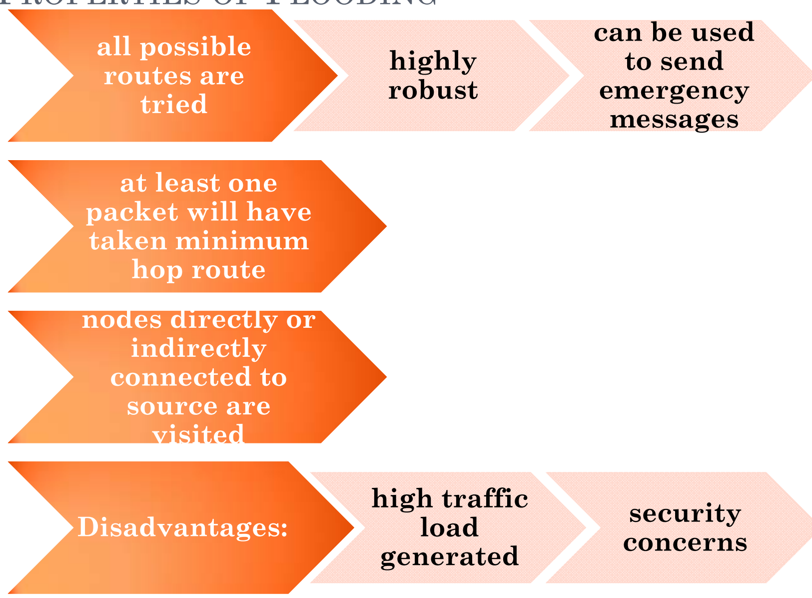
Routing Strategies - Flooding

- packet sent by node to every neighbor
- eventually multiple copies arrive at destination
- no network info required
- each packet is uniquely numbered so duplicates can be discarded
- need some way to limit incessant retransmission
  - nodes can remember packets already forwarded to keep network load in bounds
  - or include a hop count in packets

Flooding Example



PROPERTIES OF FLOODING



ROUTING STRATEGIES - RANDOM ROUTING

- simplicity of flooding with much less load
- node selects one outgoing path for retransmission of incoming packet
- selection can be random or round robin
- a refinement is to select outgoing path based on probability calculation
- no network info needed
- but a random route is typically neither 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 info about network
- disadvantages:
  - decisions more complex
  - tradeoff between quality of network info and overhead
  - reacting too quickly can cause oscillation
  - reacting too slowly means info may be irrelevant

Adaptive Routing - Advantages

- improved performance
- aid congestion control
- but since is a complex system, may not realize theoretical benefits
  - cf. outages on many packet-switched nets

Classification of Adaptive Routing Strategies

- 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

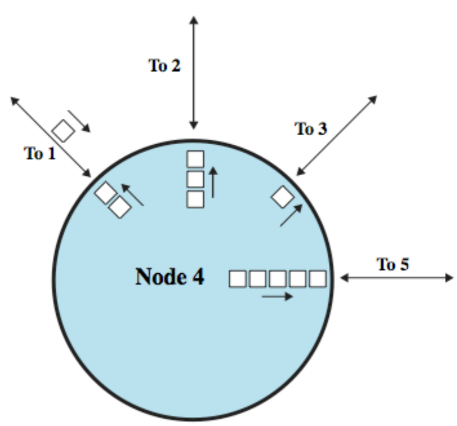
all nodes

- like adjacent

Isolated Adaptive Routing

Node 4's Bias Table for Destination 6

Next Node	Bias
1	9
2	6
3	3
5	0



ARPANET Routing Strategies 1st Generation

- designed in 1969
- distributed adaptive using estimated delay
  - queue length used as estimate of delay
- using Bellman-Ford algorithm
- node exchanges delay vector with neighbors
- update routing table based on incoming info
- problems:
  - doesn't consider line speed, just queue length
  - queue length not a good measurement of delay
  - responds slowly to congestion

ARPANET Routing Strategies 2nd Generation

- designed in 1979
- distributed adaptive using measured delay
  - using timestamps of arrival, departure & ACK times
- recomputes average delays every 10secs
- any changes are flooded to all other nodes
- recompute routing using Dijkstra's algorithm
- good under light and medium loads
- under heavy loads, little correlation between reported delays and those experienced

Oscillation

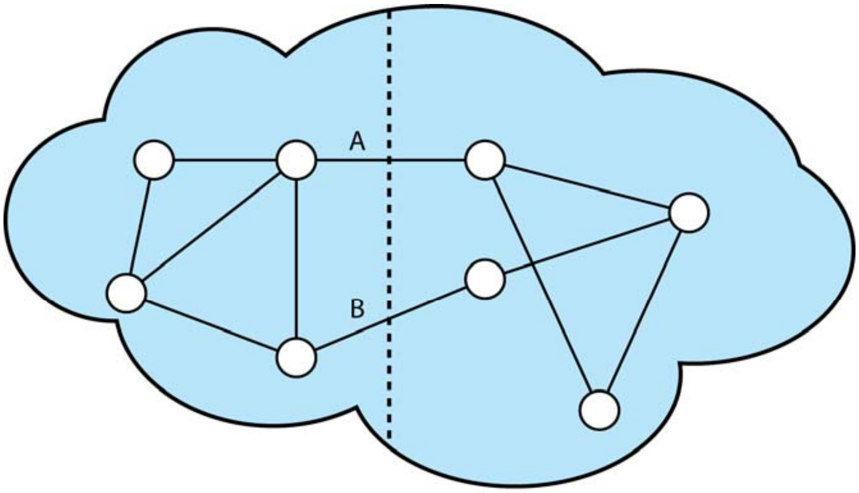


Figure 12.7 Packet-Switching Network Subject to Oscillations

ARPANET Routing Strategies 3rd Generation

- designed in 1987
- link cost calculations changed
  - to damp routing oscillations
  - and reduce routing overhead
- measure average delay over last 10 secs and transform into link utilization estimate
- normalize this based on current value and previous results
- set link cost as function of average utilization

ARPANET Delay Metrics

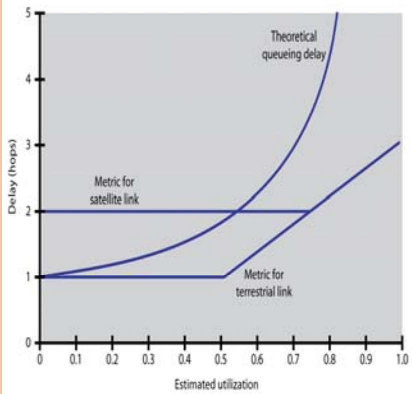
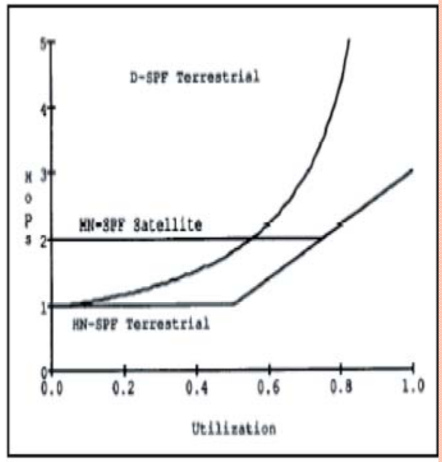


Figure 12.8 ARPANET Delay Metrics



Least Cost Algorithms

basis for routing decisions

- minimize hop with each link cost 1
- have link value inversely proportional to capacity

defines cost of path between two nodes as sum of costs of links traversed

- network of nodes connected by bi-directional links
- link has a cost in each direction

for each pair of nodes, find path with least cost

- link costs in different directions may be different

- alternatives: Dijkstra or Bellman-Ford algorithms

Least Cost Algorithms

- basis for routing decisions
  - can minimize hop with each link cost 1
  - or have link value inversely proportional to capacity
- defines cost of path between two nodes as sum of costs of links traversed
  - in network of nodes connected by bi-directional links
  - where each link has a cost in each direction
- for each pair of nodes, find path with least cost
  - nb. link costs in different directions may be different
- alternatives: Dijkstra or Bellman-Ford algorithms

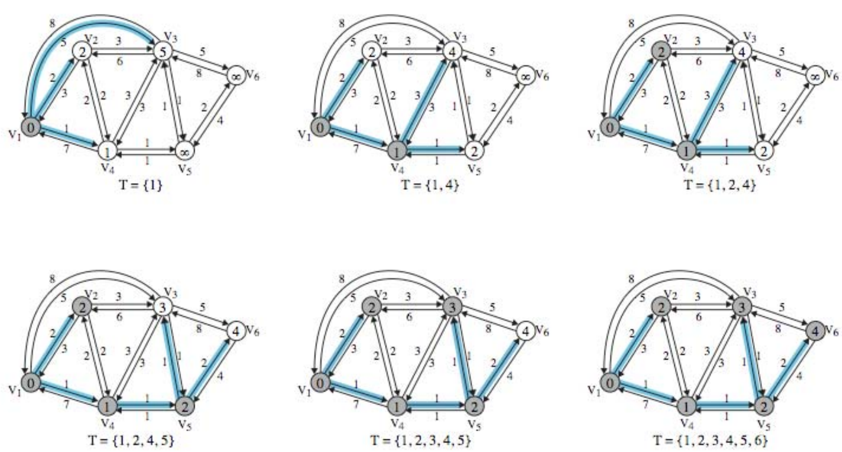
Dijkstra's Algorithm

- finds shortest paths from given source node s to all other nodes
- by developing paths in order of increasing path length
- algorithm runs in stages (next slide)
  - each time adding node with next shortest path
- algorithm terminates when all nodes processed by algorithm (in set T)

Dijkstra's Algorithm Method

- Step 1 [Initialization]
  - $T = \{s\}$ Set of nodes so far incorporated
  - $L(n) = w(s, n)$ for $n \neq s$
  - initial path costs to neighboring nodes are simply link costs
- Step 2 [Get Next Node]
  - find neighboring node not in T with least-cost path from s
  - incorporate node into T
  - also incorporate the edge that is incident on that node and a node in T that contributes to the path
- Step 3 [Update Least-Cost Paths]
  - $L(n) = \min[L(n), L(x) + w(x, n)]$ for all $n \notin T$
  - f latter term is minimum, path from s to n is path from s to x concatenated with edge from x to n

Dijkstra's Algorithm Example



Dijkstra's Algorithm Example

Iter	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

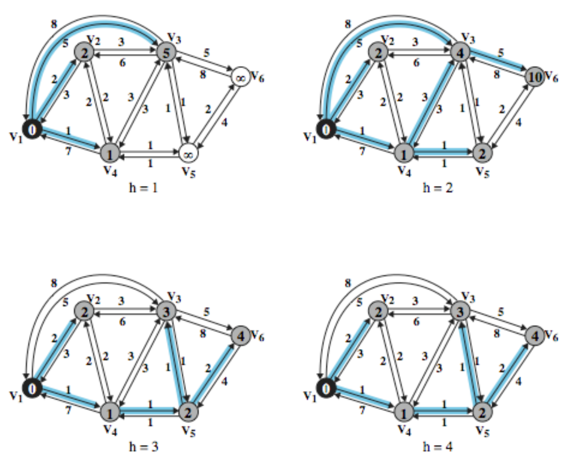
Bellman-Ford Algorithm

- find shortest paths from given node subject to constraint that paths contain at most one link
- find the shortest paths with a constraint of paths of at most two links
- and so on

Bellman-Ford Algorithm

- 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 gives min
  - 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

- results from two algorithms agree
- Bellman-Ford
  - calculation for node n needs link cost to neighbouring nodes plus total cost to each neighbour 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

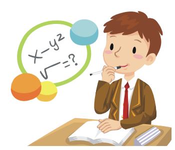
implementation specific

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-switched networks
- routing strategies
  - fixed, flooding, random,adaptive
- ARPAnet examples
- least-cost algorithms
  - Dijkstra, Bellman-Ford