Distance-vector (DV) and Path-vector (PV) scaling
- DV scales as the number of destinations $N$
- Path-vector scales approx as $N(1/2D)$, where $D$ is the network diameter
  - Because paths are one average $1/2$ the diameter
  - A single link change can still result in large updates
    - (all destinations for which there is a new path)
  - So overhead can vary depending on situation (unpredictable)

Distance-path overhead example
- Node $X$ doesn't see dashed links
- What if link $x$--$a$ goes down?

One link change can result in updates about many destinations
- $X$ has to "learn" all of these paths
- Updates about 7 destinations!
Distance-vector problems

- As we saw, distance-vector (DV) routing algorithms, while simple, suffer from slow convergence
- Path-vector (PV) fixes most of this, but still has some unpredictability
- Link State pre-dates PV, is less flexible but has very fast convergence and predictable overheads
  - In wide use: OSPF

Link-State approach

- Like PV, LS works by providing more explicit information about the state of the network
  - In fact, complete information about the state of the network!
- Every node knows about every link
  - Internally contains a “map” of the complete network
- From this map, each node computes its next hops

Link State Operation

- Each node floods the status of all of its links to every other node
  - This creates the RIB
- Each node generates its FIB by running a shortest-path spanning tree algorithm with itself as the root
Flooding
- Each node periodically floods a Link State Update (LSU) to all nodes
  - Or immediately if a link changed
- LSU contains:
  - List of all the node's links and costs
  - A sequence number (to determine which LSU is the most recent
  - A hop count

Flooding algorithm (simplified)
- Each node stores the latest LSU seq num (SNs) received for all nodes
- When a node originates an LSU, it increments the SN
- When an LSU is received, if the received SNr is “newer than” SNs, then:
  - Record information in LSU
  - Send LSU to all neighbors
  - Set SNs = SNr
- Otherwise, ignore the LSU

Sequence number initialization and wrap around
- This is far trickier than you’d think…
- Imagine an 8-bit unsigned sequence number (0 <= SN <= 0xff)
- Say SNs = 0xf0, and SNr = 0x0f
- Is the received LSU newer or older than the stored one?
Sequence number initialization and wrap around

- When SN reaches max value, it will wrap around to 0
  - Thus, at some point, SN=0 is "newer than" SN=0xFFFF
- SNs = 0xf0, and SNr = 0x0f
- Probably SNr is newer, but you can't be sure
  - Maybe there is some error that caused a router to send an old SN

Approach number 1: circular seq num space

- To compare two numbers a and b
  - Divide seq space in half at a
  - If b is in clockwise half, then b is newer, else a is newer
- Router must save its own SN in non-volatile memory (disk)
- When router restarts, initialize own SN to latest saved value + 1

Circular seq num space

One problem with circular seq num space

- These SLU's would flood forever…
  - Or until the hop count expired
- This apparently happened in the ARPANET
Approach number 2: Huge linear seq num space
- 64-bit sequence number space, no wrap-around
- Store own SN in non-volatile memory, init from most recent SN + 1
- When max value reached \((2^{64}-1)\), crash!!!
- At 100 LSU/sec, takes 6 billion years to hit max (i.e. never crash)

Problem with huge linear seq num space
- Try explaining it to customers…
- Non-volatile storage must be very reliable
  - Disk, for instance, is not that reliable
- If the SN is lost, router must be restarted as a different router (i.e. with a different identity)

Approach number 3: Lollipop shaped seq num space
- Initial sequence: 0 \(\rightarrow a-1\)
- Circular space: \(a\to\text{max} 1\) newer than 0
- \(a-1\) newer than \(a-2\)
- \(a-1\) newer than \(a\)

Problems with lollipop shaped seq num space
- Same \(a < b < c < a\) problem
  - Though this is mitigated by hop count in LSU
- If router restarts before \(SN \geq a\), then no new LSUs will be recognized until new SN reaches old high-water
  - But routers with bugs may often restart shortly after startup
- This approach in V1 of OSPF
Approach 4: Linear space with LSU flush
- Used by OSPF V2
- Extra bit in LSU used to indicate that last LSU should be flushed
- When router restarts, it flushes max SN, then sends initial LSU with SN=0
  - Likewise, if SN wraps, flush max SN before wrap
- Problem would occur if flush not received by all nodes
  - But OSPF flood is quite reliable (LSUs are ACK'd)

Shortest path calculation
- After any change in the network, the shortest path algorithm is run on the "graph" to calculate the next hops for the FIB
- Attributed to Dijkstra
- All routers must run exactly the same algorithm
  - So that they calculate consistent shortest paths

Shortest path algorithm (1/2)
- Maintain 2 lists, confirmed and tentative
  - Each entry has <dest, cost, nexthop>
- To initialize, add self to confirmed
- In each round of the algorithm:
  - One dest is moved from tentative to confirmed
  - Zero or more dests are moved into tentative

Shortest path algorithm (2/2)
- next = node just moved into confirmed
  - Calculate costs to all of next's neighbors (as next_cost + link_cost)
    - Add neighbor to tentative if not there
    - Change entry in tentative if new cost is lower
  - Move node with lowest cost from tentative to confirmed
  - Repeat until tentative is empty
Shortest path algorithm optimizations

- Finding the lowest-cost node in the tentative list is expensive
  - Maintain bins for different ranges of cost
  - Only need to search lowest-cost non-empty bin
- Maintain full tree (as predecessor nodes)
  - If non-tree link increases, do nothing
  - In other cases, can pre-populate confirmed and tentative lists

Routing update packet priority

- Routing updates should have higher priority than data packets
  - So that they get through during congested periods
- But routing updates should be rate limited
  - So that an erroneous flood of updates doesn’t starve the network
  - Nodes rate limit their neighbors as well as themselves