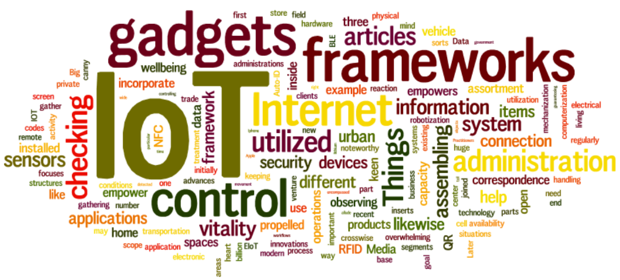
CS578: Internet of Things

RPL: Routing over Low-Power and Lossy Networks

RFC 6550: https://tools.ietf.org/html/rfc6550



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"The Man who works for others, without any selfish motive, really does good to himself." – **Shri Ramakrishna**

What is LLN?

RFC 7228

- **Constrained Node**: A node where some of the characteristics that are otherwise pretty much taken for granted for Internet nodes are not attainable, often due to cost constraints and/or physical constraints on characteristics such as size, weight, and available power and energy.
  - tight limits on **power**, **memory**, and **processing resources**

- **Constrained Network**: A network where some of the characteristics pretty much taken for granted with link layers in common use in the Internet are not attainable.
  - low achievable **bitrate/throughput**; high **packet loss** and variability of packet loss; limits on reachability over **time**

- **Constrained-Node Network**: A network whose characteristics are influenced by being composed of a significant portion of constrained nodes.

- **LLN (Low-Power and Lossy Network):** Typically composed of many embedded devices with limited power, memory, and processing resources interconnected by a variety of links, such as IEEE 802.15.4 or low-power Wi-Fi.

Routing challenges in LLNs

- Energy consumption is a major issue (for battery powered sensors/controllers)
- Limited processing power
- Very dynamic topologies
  - Link failure (Low-powered RF)
  - Node failures
  - Node mobility (in some environments)

- Data processing usually required on the node itself,
- Sometimes deployed in harsh environments (e.g. Industrial),
- Potentially deployed at very large scale,
- Must be self-managed network (auto-discovery, self-organizing,)

Can’t use OSPF, OLSR, RIP, AODV, DSDV, DSR, etc

Routing Over Low power and Lossy link (ROLL) WG

- ROLL Working Group Formed in Jan 2008

- **Mission**: define Routing Solutions for LLN
  - Should be able to operate over a variety of different link layer technologies

- Work Items:
  - Routing Protocol work
  - Routing is designed to support different LLN application requirements
    - RFC 5548 - Routing requirements for Urban LLNs
    - RFC 5673 - Routing requirements for Industrial LLNs
    - RFC 5826 - Routing requirements for Home Automation LLNs
    - RFC 5867 - Routing requirements for Building Automation LLNs
  - Routing metrics for LLN
  - Produce a security Framework
  - Applicability statement of ROLL routing protocols

- Proposed protocol: **RPL (IPv6 Routing Protocol for LLNs)**

RPL is a ……

- Distance Vector (DV) protocol
- Source Routing Protocol

What is a Distance Vector (DV) protocol?

- The term distance vector refers -
  - protocol manipulates vectors of distances to other nodes in the network
- Distance-vector protocols are based on calculating the Direction and Distance to any node/link in a network.
  - "Direction" usually means the next hop address and the exit interface.
  - "Distance" is a measure of the cost to reach a certain node.

- Least cost route between any two nodes is the route with minimum distance.
- Each node maintains a vector (table) of minimum distance to every node.
- Requires that a router inform its neighbours of topology changes periodically

- Intra-domain routing protocol (i.e. inside a AS)
- Have less computational complexity and message overhead

Cont…

What is a Source Routing (path addressing) protocol?

- Allows a sender of a packet to partially or completely specify the route the packet takes through the network.
- Enables a node to discover all the possible routes to a host.

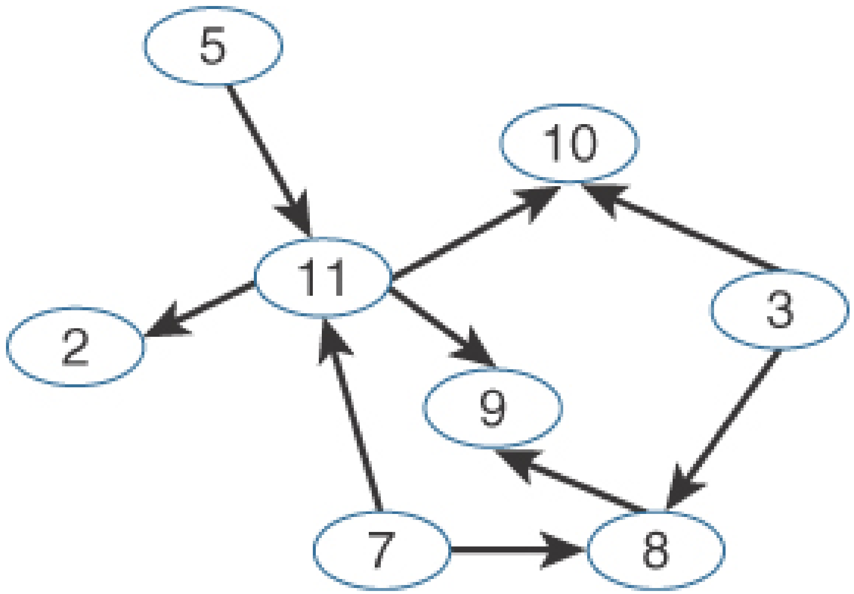
Two modes of RPL:

- **Storing mode:**
  - All nodes contain the full routing table of the RPL domain.
  - Every node knows how to directly reach every other node.

- **Non-storing mode:**
  - Only the border router(s) of the RPL domain contain(s) the full routing table.
  - Boarder router knows how to directly reach every other node.

RPL Topology (1/2)

RPL organizes a topology as a DAG

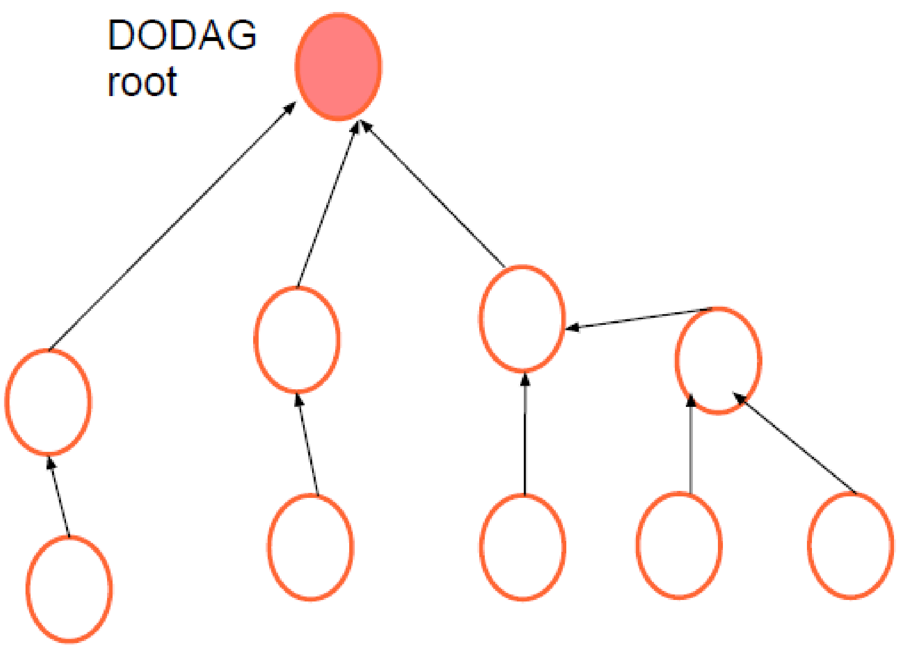


DAG(Directed Acyclic Graph)

- A DAG is a directed graph where no cycles exist.

RPL Topology (2/2)

- A DAG rooted at a single destination at a single DAG root (DODAG root) with no outgoing edges

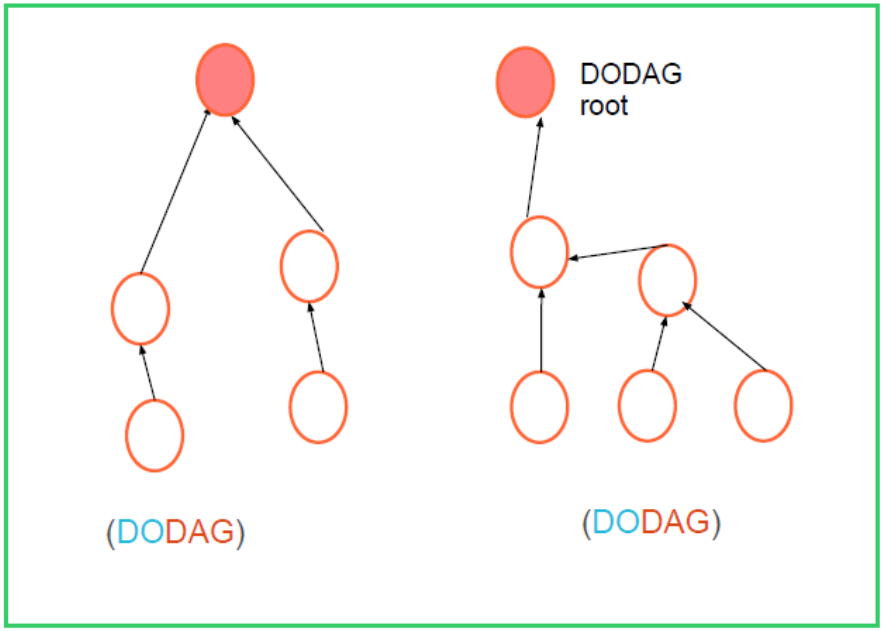


DODAG (Destination Oriented DAG)

- A basic RPL process involves building a DODAG.
- In RPL, this destination occurs at a border router known as the DODAG root.
- Simplest RPL topology: single DODAG with one root
- Complex scenario: multiple uncoordinated DODAGs with independent roots
- More sophisticated and flexible configuration: single DODAG with a virtual root that coordinates several LLN root nodes

RPL Instance

- A RPL Instance is a set of one or more DODAGs that share a RPLInstanceID.



RPL Instance

- **RPLInstanceID** is a **unique** identifier within a network.
- DODAGs with the same RPLInstanceID share the same Objective Function (OF) used to compute the position of node in the DODAG .
- An **objective function** (OF) defines how metrics are used to select **routes** and establish a node's **rank**.
  - RFC 6552 and RFC 6719
- Objective Function computes the "**rank**" measuring the "distance" between the node and DODAG root
- *Rank* should monotonically decrease along the DODAG and towards the destination

RPL Control Messages

1) DODAG Information Object (**DIO**):
   - Downward RPL instance multicasts
   - Allows other nodes to discover an RPL instance and join it

2) DODAG Information Solicitation (**DIS**):
   - Link-Local multicast request for DIO (i.e. neighbor discovery).
   - Do you know of any DODAGs, asked by a node?

3) Destination Advertisement Object (**DAO**):
   - From child to parents or root
   - Can I join you as a child on DODAG #x?

4) DAO-ACK: Yes, you can! Or Sorry, you cant!

5) Consistency Check (**CC**): Challenge-response messages for security

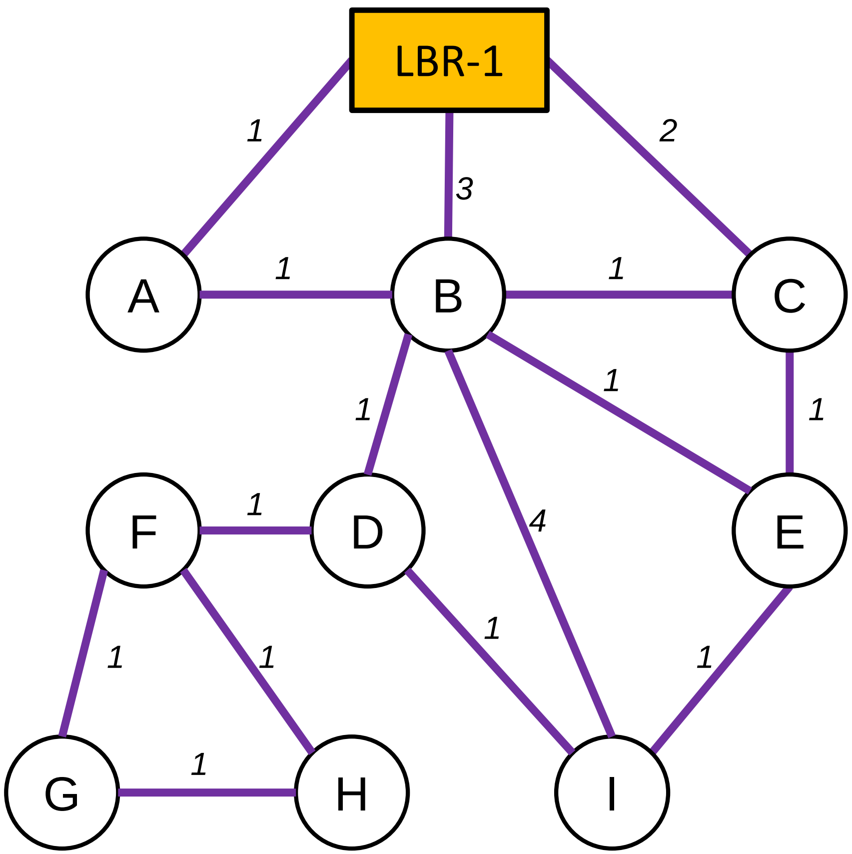
RPL Traffic Types

1) MP2P : Multipoint-to-Point
   - is the dominant traffic in many LLN applications.
   - usually routed towards destination nodes such as LLN gateway
   - these destinations are the DODAG roots, and they act mainly as data collection points

2) P2MP: *Point-to-Multipoint*
   - data streams can be used for actuation purposes
   - messages sent from DODAG roots to destination nodes

3) P2P: *Point-to-Point*
   - to allow communications between two devices belonging to the same LLN

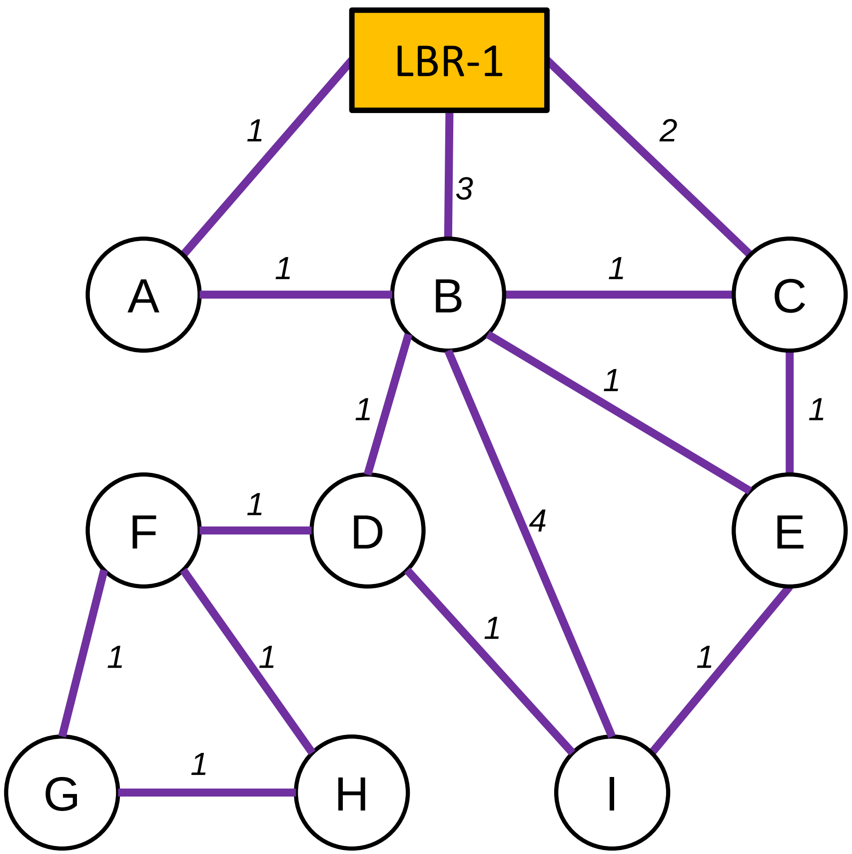
DAG Construction (1/9)



- LLN links are depicted
- RPL Objective functions:
  - ETX https://tools.ietf.org/html/draft-gnawali-roll-etxof-00
  - OF0 https://tools.ietf.org/id/draft-ietf-roll-of0-14.html
- Links are annotated w/ ETX
- It is expected that ETX variations will be averaged/filtered as per ROLL Metrics to be stable enough for route computation
  - Nodes observe the metric and gain confidence before use

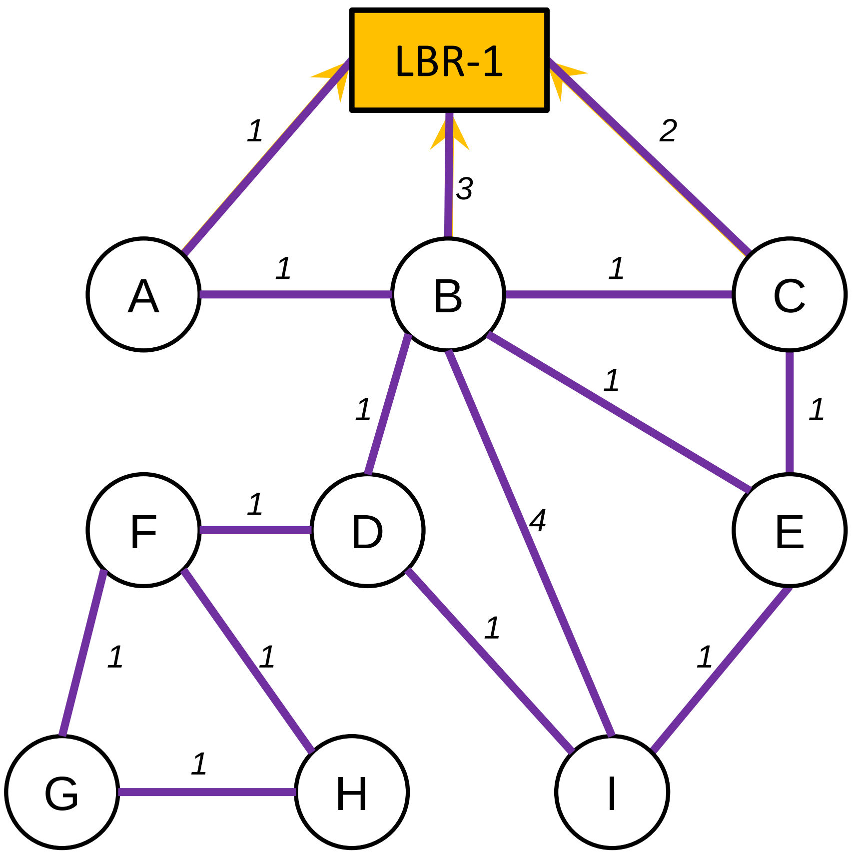
The ETX metric of a wireless link is the expected number of transmissions required to successfully transmit and acknowledge a packet on the link.

DAG Construction (2/9)



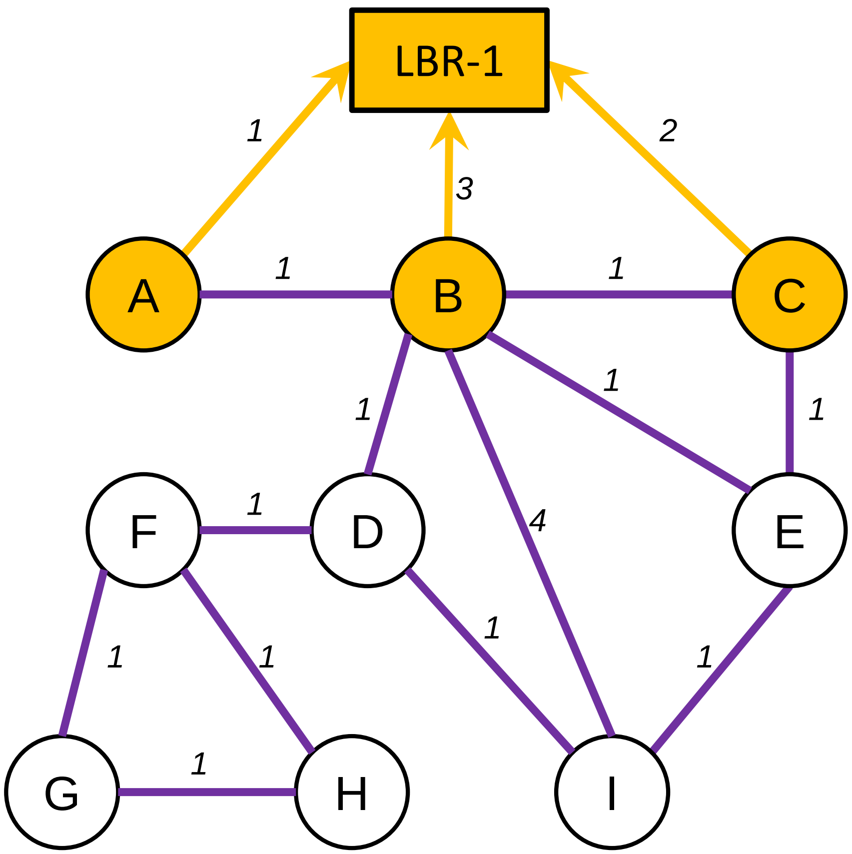
- Objective Code Point (OCP) for example
  - Metric: ETX
  - Objective: Minimize ETX
  - Depth computation: Depth ~ ETX
    - Note that a practical computation may be more coarse

DAG Construction (3/9)



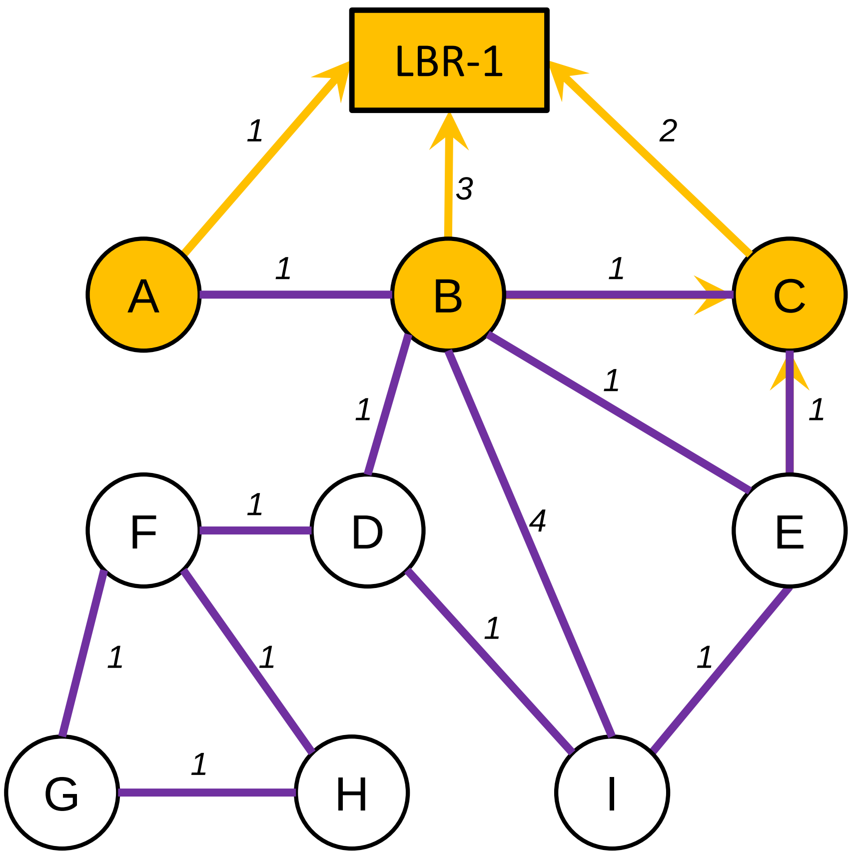
- LBR-1 multicasts RA-DIO (i.e. router advertisement using DIO)
- Nodes A, B, C receive and process RA-DIO
- Nodes A, B, C consider link metrics to LBR-1 and the optimization objective
- The optimization objective can be satisfied by joining the DAG rooted at LBR-1
- Nodes A, B, C add LBR-1 as a DAG parent and join the DAG

DAG Construction (4/9)



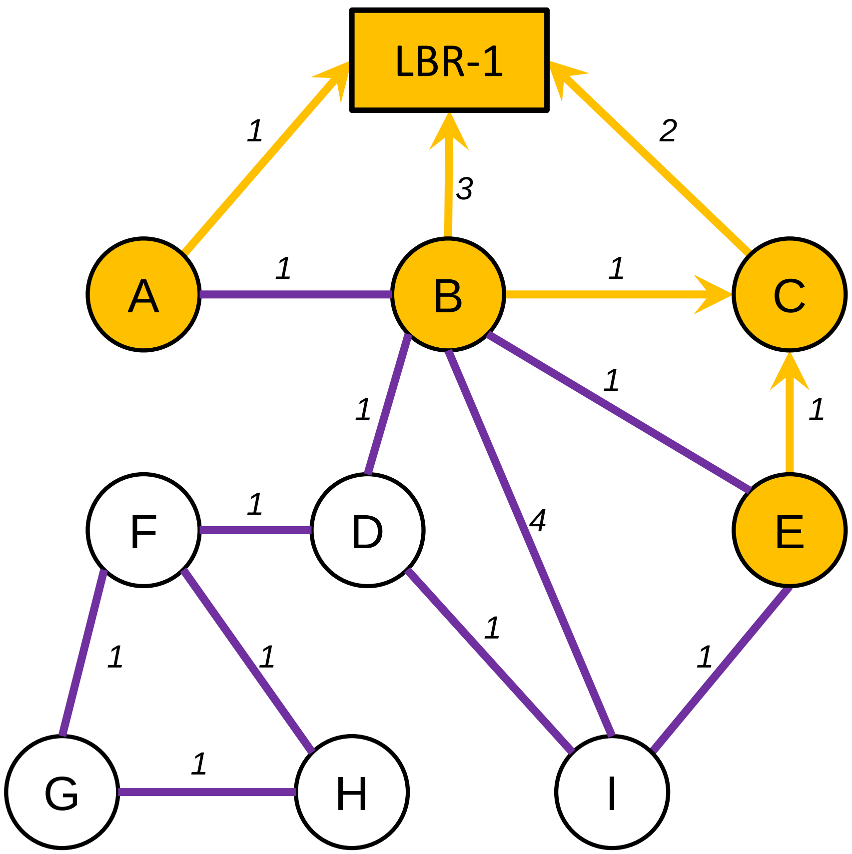
- Node A is at Depth 1 in the DAG, as calculated by the routine indicated by the example OCP (Depth ~ ETX)
- Node B is at Depth 3, Node C is at Depth 2
- Nodes A, B, C have installed default routes (::/0) with LBR-1 as successor
- **Note**: An arrow shows who is your parent. But, the links are bidirectional.

DAG Construction (5/9)



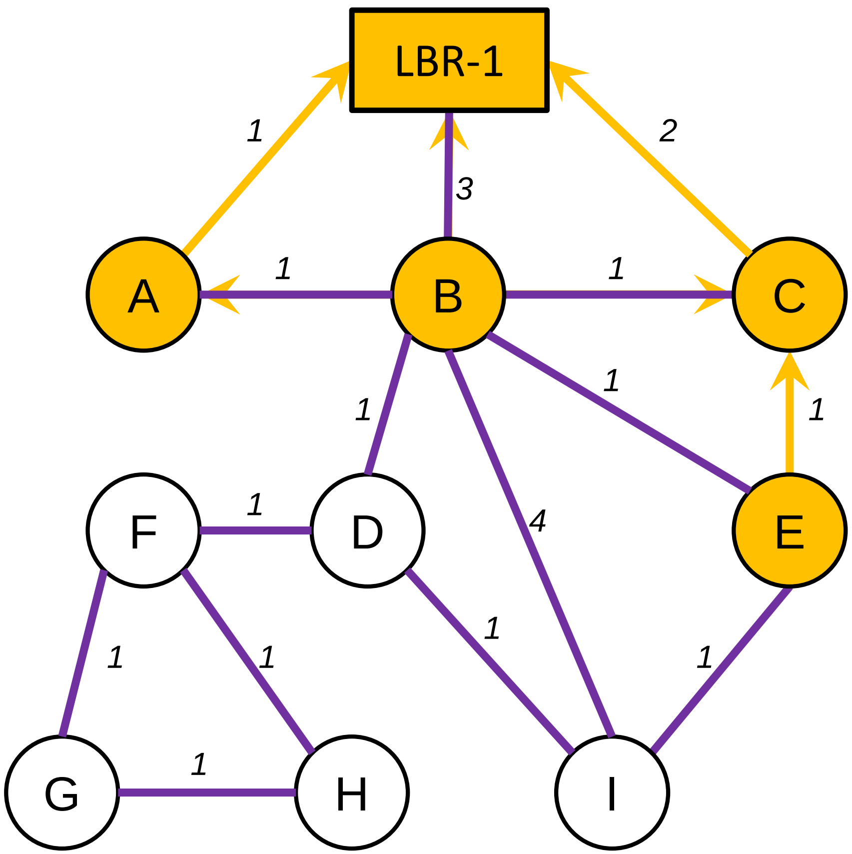
- The RA timer on Node C expires
- Node C multicasts RA-DIO
- LBR-1 ignores RA-DIO from deeper node
- Node B can add Node C as *alternate* DAG Parent, remaining at Depth 3
- Node E joins the DAG at Depth 3 by adding Node C as DAG Parent

DAG Construction (6/9)



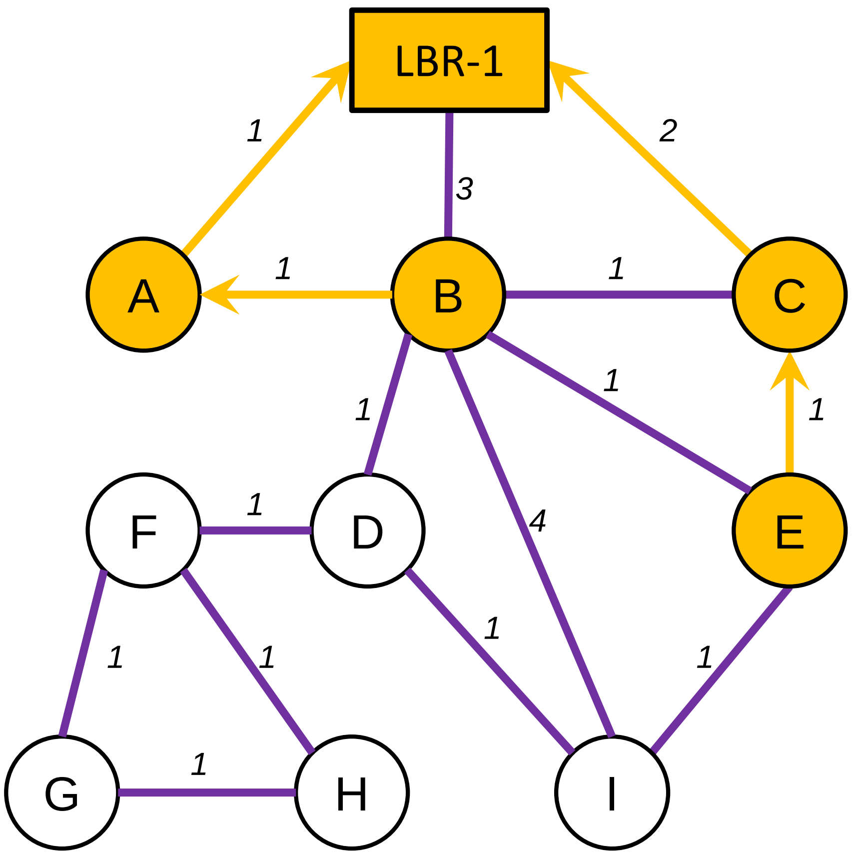
- Node A is at Depth 1, and can reach ::/0 via LBR-1 with ETX 1
- Node B is at Depth 3, with DAG Parents LBR-1, and can reach ::/0 via LBR-1 or C with ETX 3
- Node C is at Depth 2, ::/0 via LBR-1 with ETX 2
- Node E is at Depth 3, ::/0 via C with ETX 3

DAG Construction (7/9)



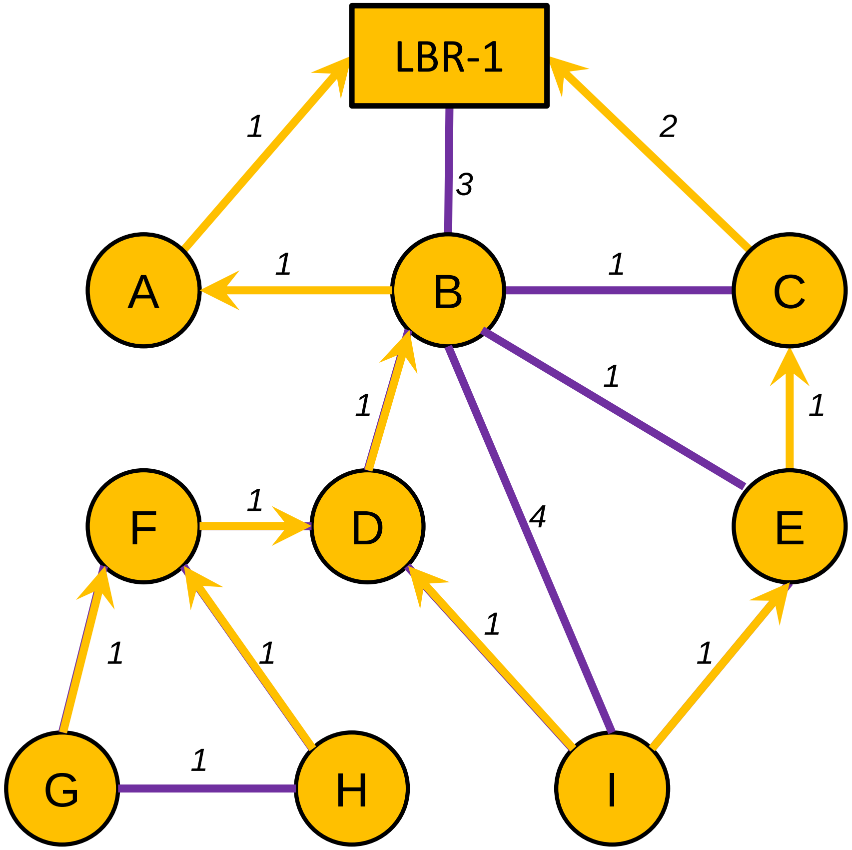
- The RA timer on Node A expires
- Node A multicasts RA-DIO
- LBR-1 ignores RA-DIO from deeper node
- Node B adds Node A
- Node B can improve to a more optimum position in the DAG
- Node B *removes* LBR-1 and Node C as DAG Parents

DAG Construction (8/9)



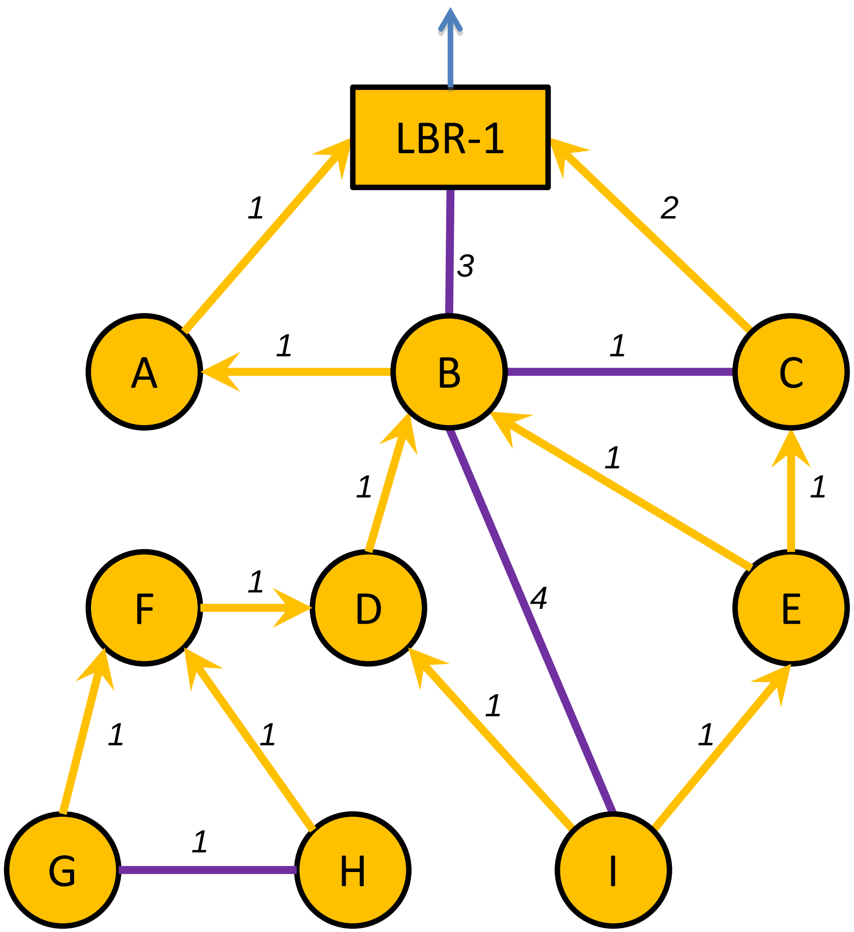
- Node A is at Depth 1, ::/0 via LBR-1 with ETX 2
- Node B is at Depth 2, ::/0 via A with ETX 2
- Node C is at Depth 2, ::/0 via LBR-1 with ETX 2
- Node E is at Depth 3, ::/0 via C with ETX 3

DAG Construction (9/9)



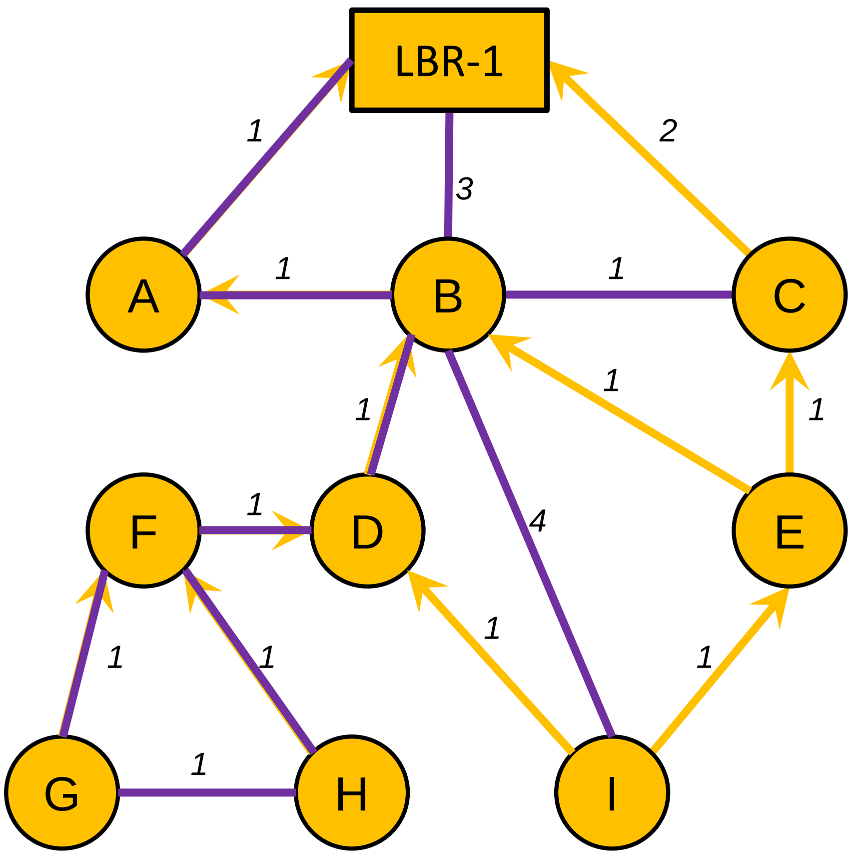
- DAG Construction continues…
- And is continuously maintained

MP2P Traffic



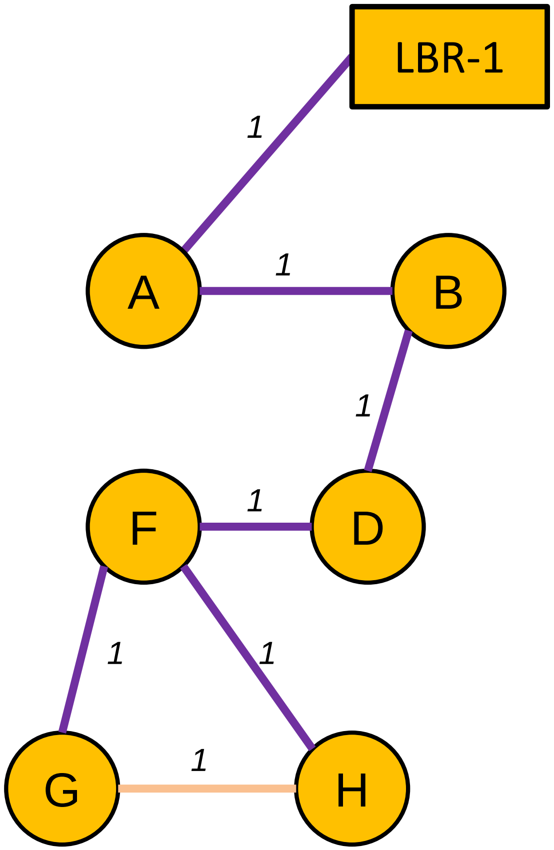
- MP2P traffic flows inwards along DAG, toward DAG Root
- DAG Root may also extend connectivity to other prefixes beyond the DAG root, as specified in the DIO
- Nodes may join multiple DAGs as necessary to satisfy application constraints

Destination Advertisements (1/7)



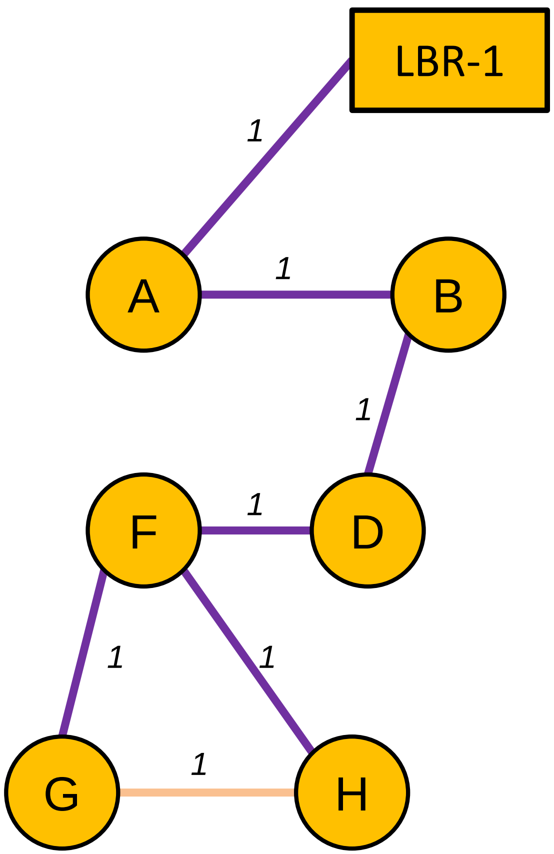
- Destination Advertisements (DAs) build up routing state in support of P2MP traffic flows outward, from the sink to other nodes
- DA uses the same DAG
- For simplicity, we will focus on a subset of DA in the example

Destination Advertisements (2/7)



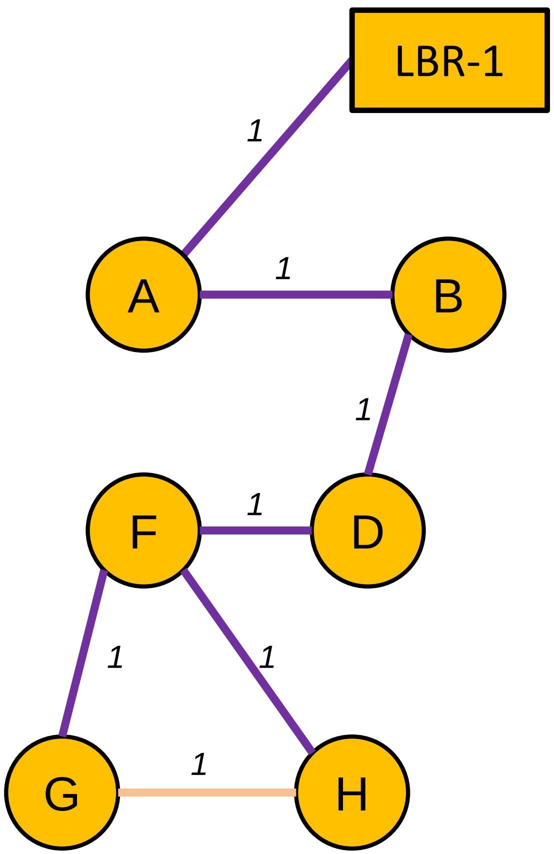
- Some nodes may be able to store routing state for outward flows (LBR-1, A, F)
- Some nodes may not (B, D)
- Some nodes may have a limited ability;
- DAs may indicate a priority for storage
- DAs may be triggered by DAG root or node who detects a change
- DA timers configured such that DAs start at greater depth, and may aggregate as they move up

Destination Advertisements (3/7)



- LBR-1 triggers Destination Advertisement (DA) mechanism in DIO
- G emits neighbor advertisement (NA) to F with DAO indicating reachability to destination prefix G::
- F stores G:: via G
- H emits NA to F for destination prefix H::
- F stores H:: via H

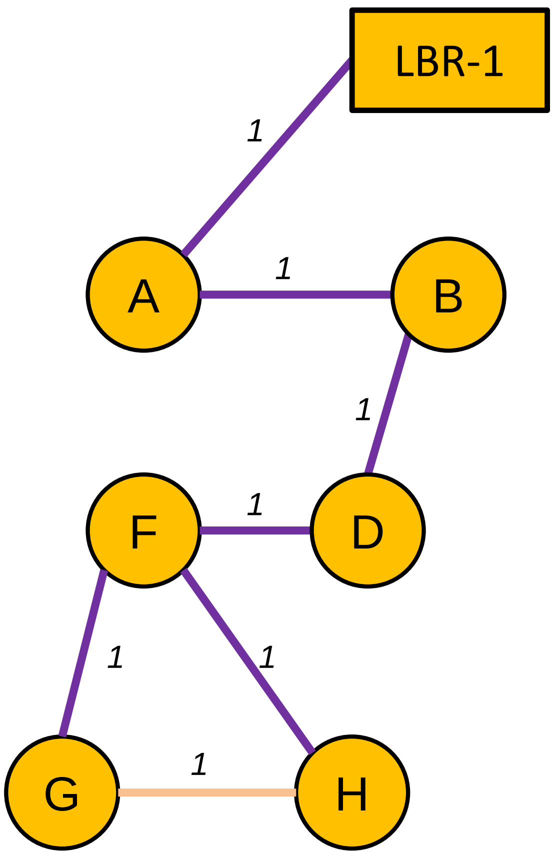
Destination Advertisements (4/7)



- Suppose in this example F has a prefix F*:: capable of aggregating {F::, G::, H::}
  - The method to provision such a prefix is beyond the scope of RPL
- F emits NA to D with DAO indicating reachability to destination prefix F*::
- D cannot store…

(continued)

Destination Advertisements (5/7)



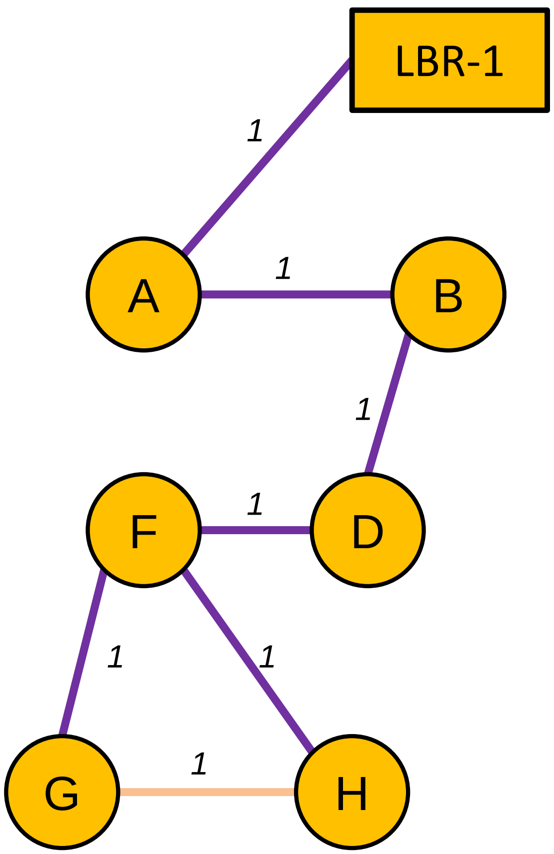
- D adds F to the Reverse Route Stack in the DAO, and passes DAO on to B for F*:: [F]

- D also emits a DAO indicating prefix D:: to B

- B cannot store routing state…

(continued)

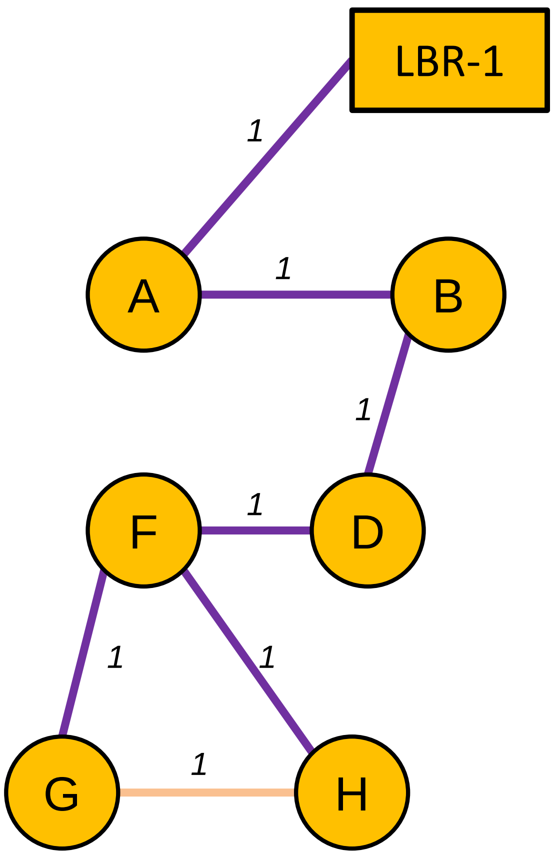
Destination Advertisements (6/7)



- B adds D to the Reverse Route Stack in the DAO for D::, and passes DAO D:: [D] on to A
- A stores D:: via B, with the piecewise source route [D]
- B also emits a DAO indicating prefix B:: to A
- A stores B:: via B

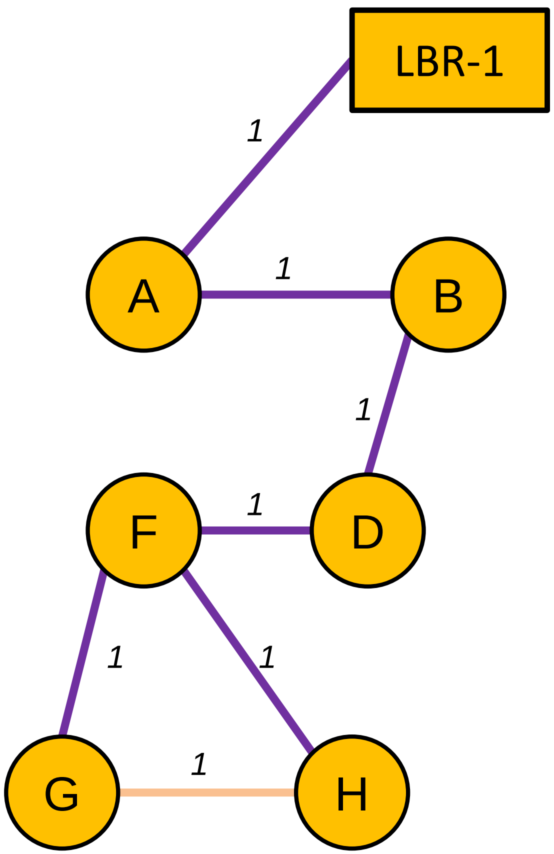
(continued)

Destination Advertisements (7/7)



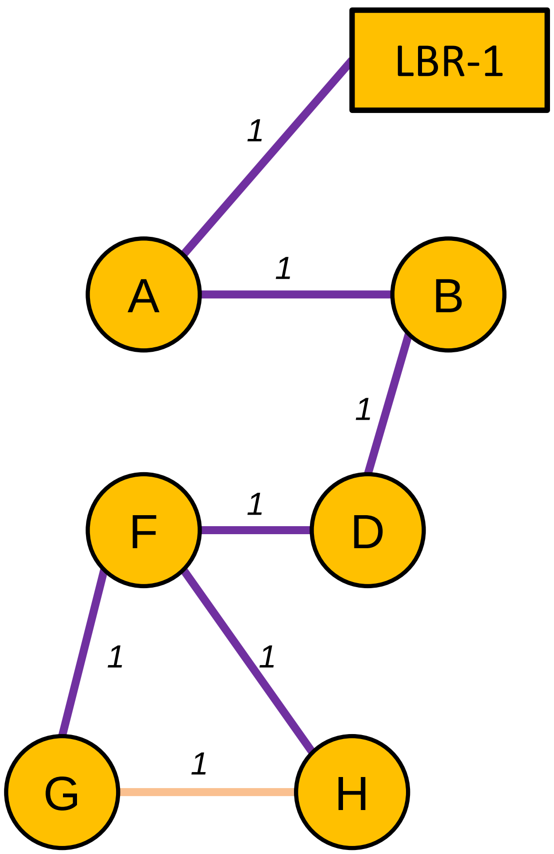
- A emits DAOs to LBR-1 for destination prefixes A::, B::, D::, and F*
- LBR-1 stores A:: via A, B:: via A, D:: via A, and F*:: via A
- A stored B:: via B, D:: via B [D], F* via B [D, F]
- B, D stored nothing
- F stored G:: via G, H:: via H

P2MP Traffic (1/2)



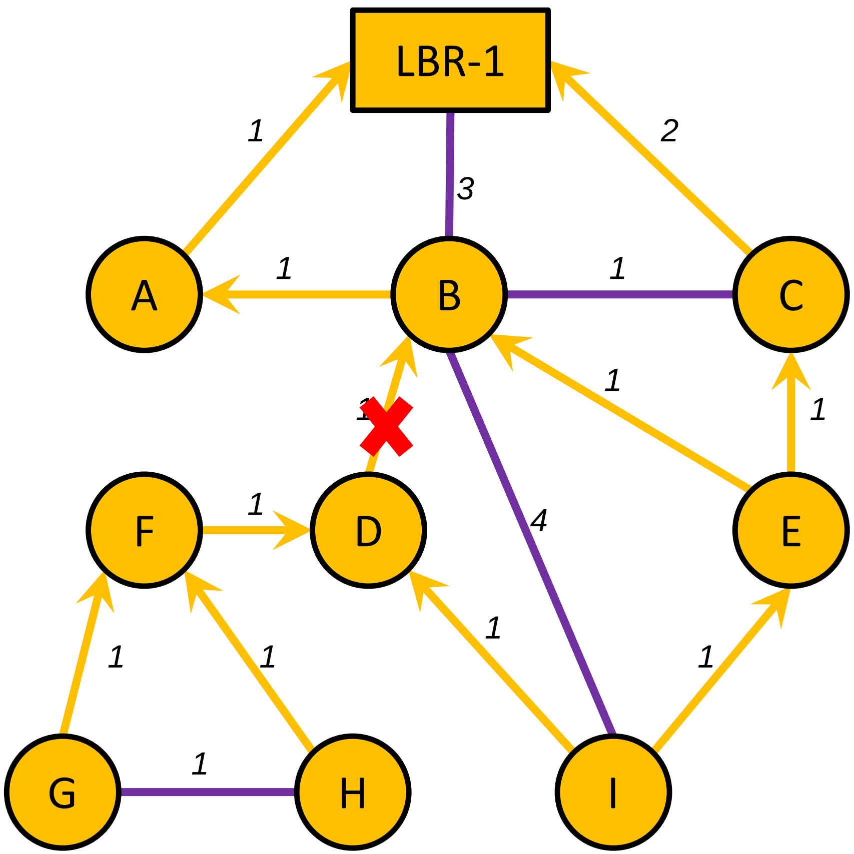
- The routing state setup by Destination Advertisement is used to direct P2MP traffic outward
- LBR-1 directs traffic for G (F*::) to A
- A adds source routing directive, [D, F], and forwards to B
- B uses source routing directive to forward to D...

P2MP Traffic (2/2)



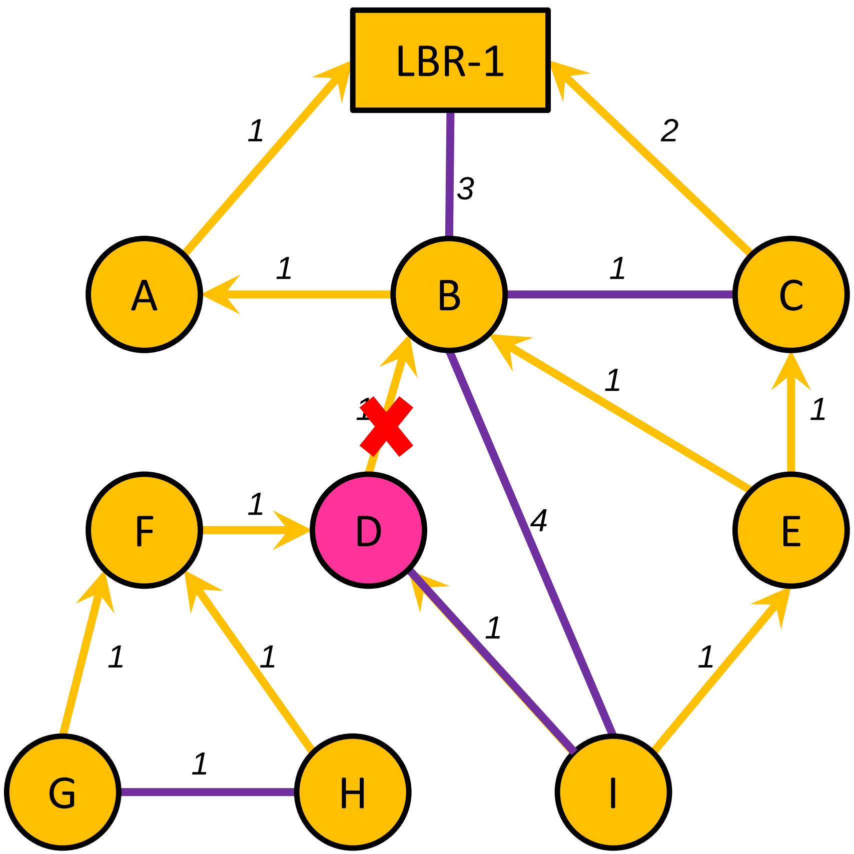
- D uses source routing directive to forward to F
- F uses routing state to forward to G
- Note the use of source routing to traverse the stateless region of the LLN

DAG Maintenance (1/10)



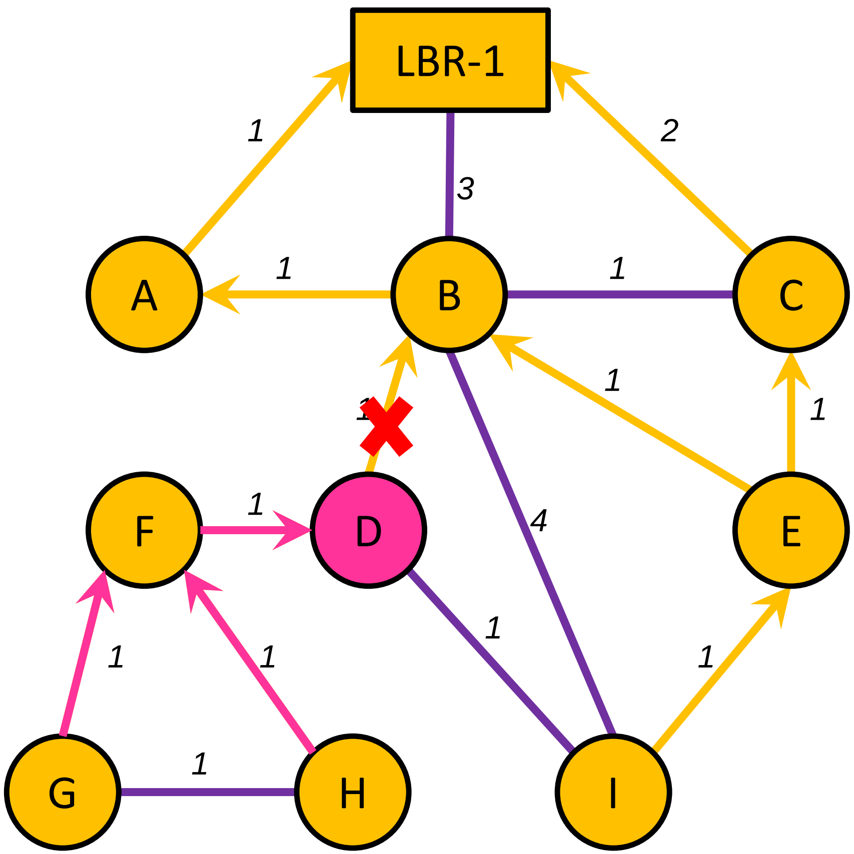
- Consider the case where the link B—D goes bad
- Node D will remove B from its DAG parent set
- Node D no longer has any DAG parent in the grounded DAG, so it will become the root of its own floating DAG

DAG Maintenance (2/10)



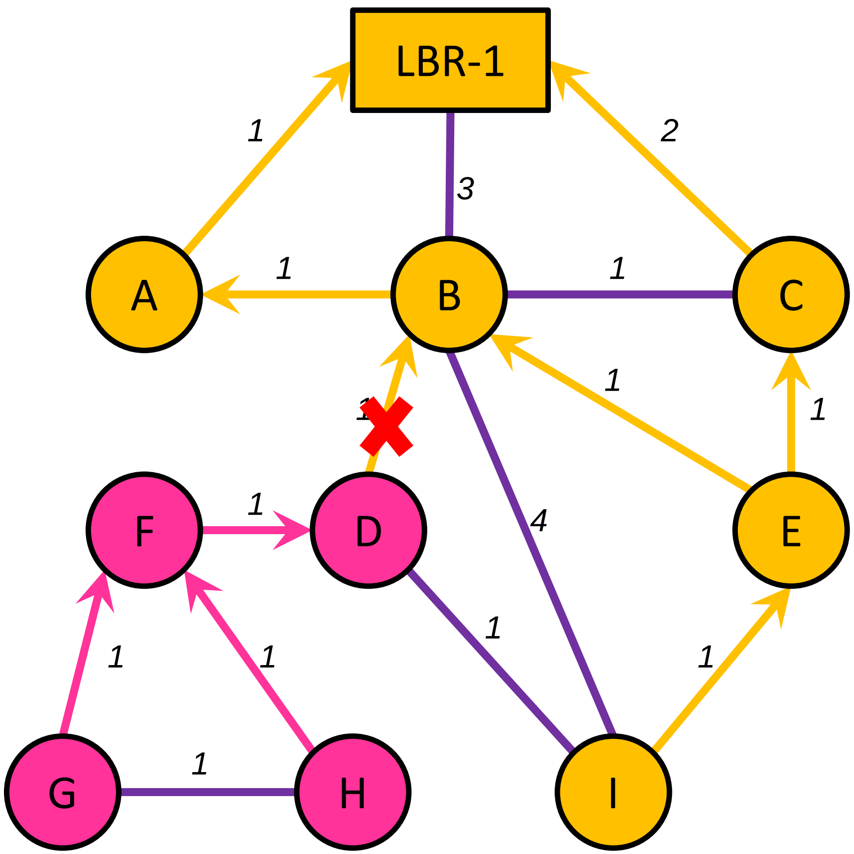
- Node D multicasts an RA-DIO to inform its sub-DAG of the change
- Node I has an alternate DAG Parent, E, and does not have to leave the DAG rooted at LBR-1.
- Node I removes Node D as a DAG Parent

DAG Maintenance (3/10)



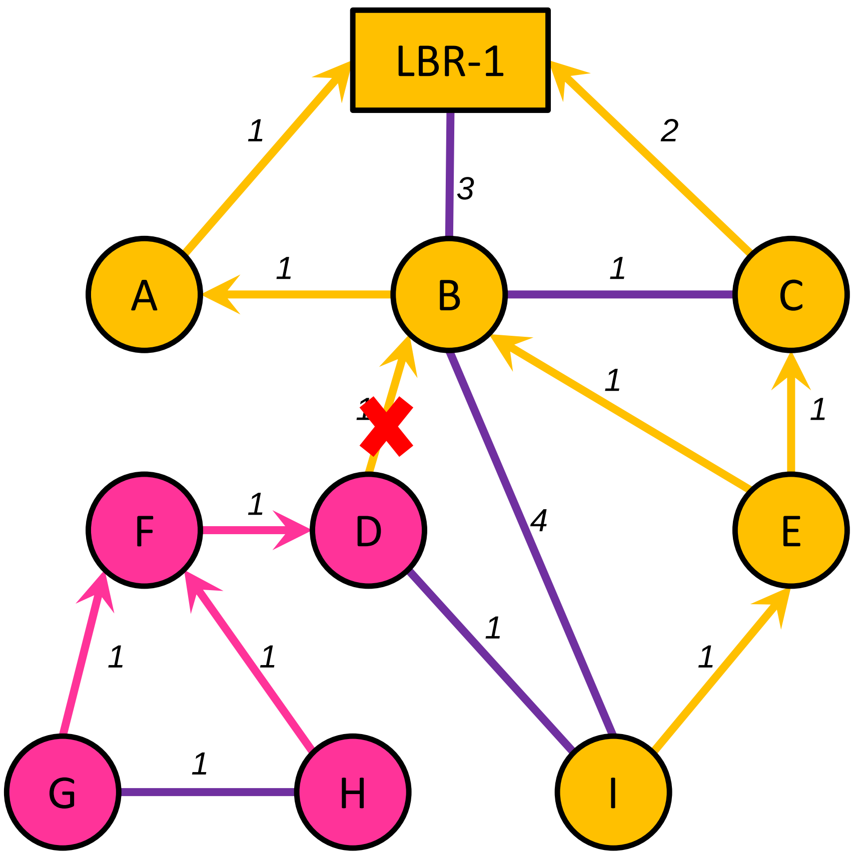
- Node F does not have an option to stay in the DAG rooted at LBR-1 (no alternate DAG Parents),
- So, Node F follows Node D into the floating DAG
- Node F multicasts an RA-DIO
- Nodes G and H follow Node F into the floating DAG

DAG Maintenance (4/10)



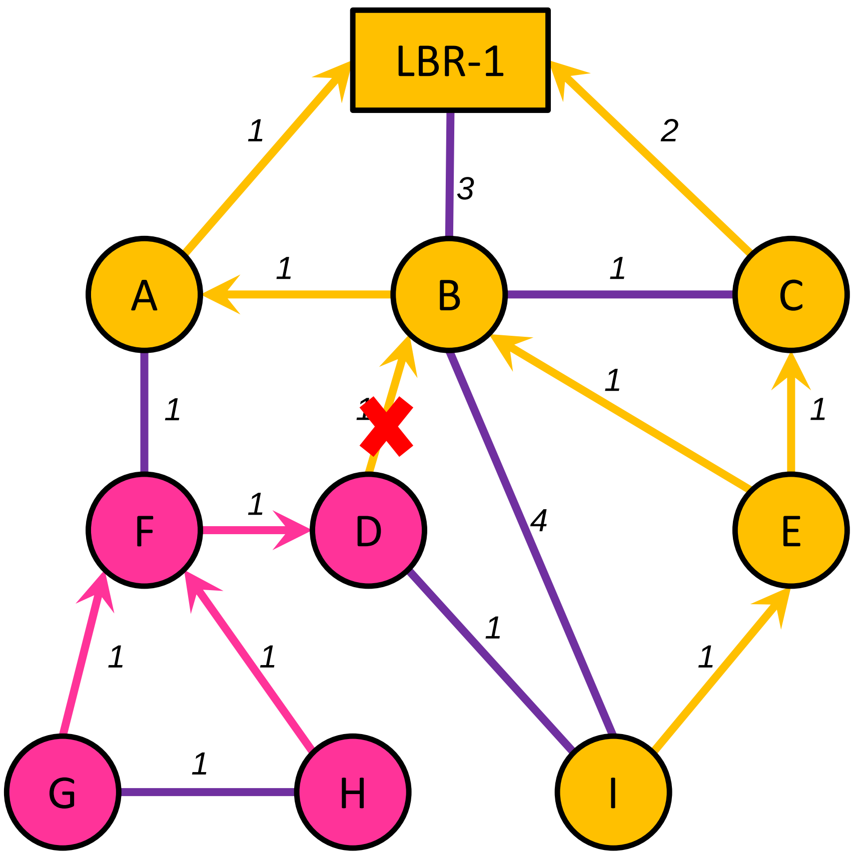
- The sub-DAG of node D has now been frozen
- Nodes contained in the sub-DAG have been identified, and by following node D into the floating DAG, all old routes to LBR-1 have been purged
- The floating DAG seeks to rejoin a grounded DAG…

DAG Maintenance (5/10)



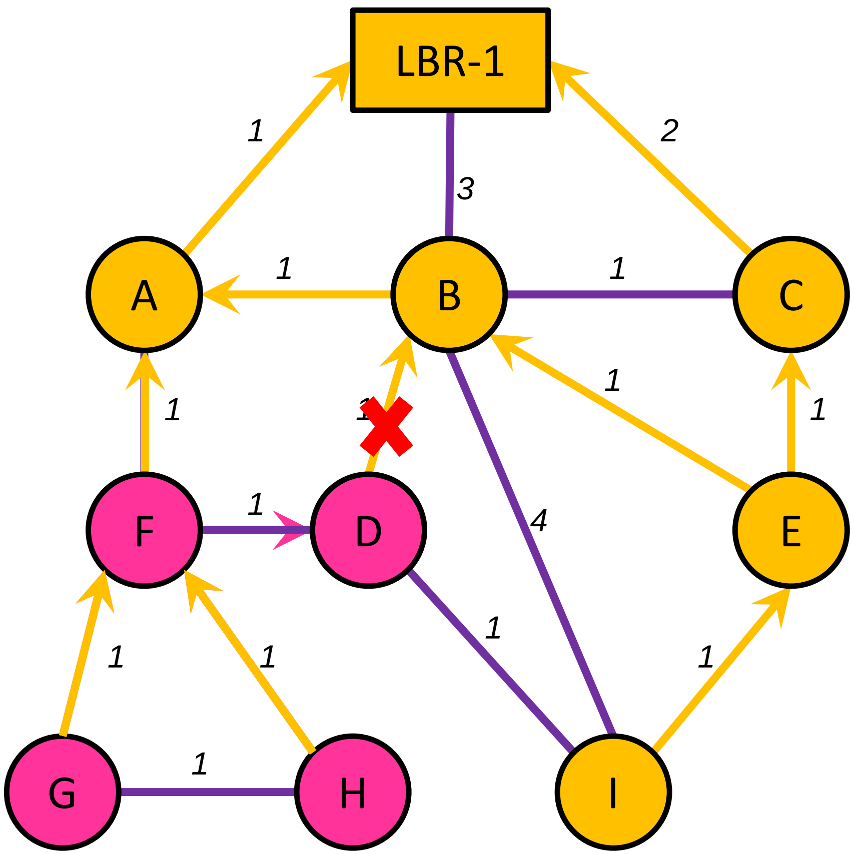
- Node I multicasts an RA-DIO
- Node D sees a chance to rejoin grounded DAG at depth 5 through Node I
- Node D starts a DAG Hop timer of duration α 4 associated with Node I

DAG Maintenance (6/10)



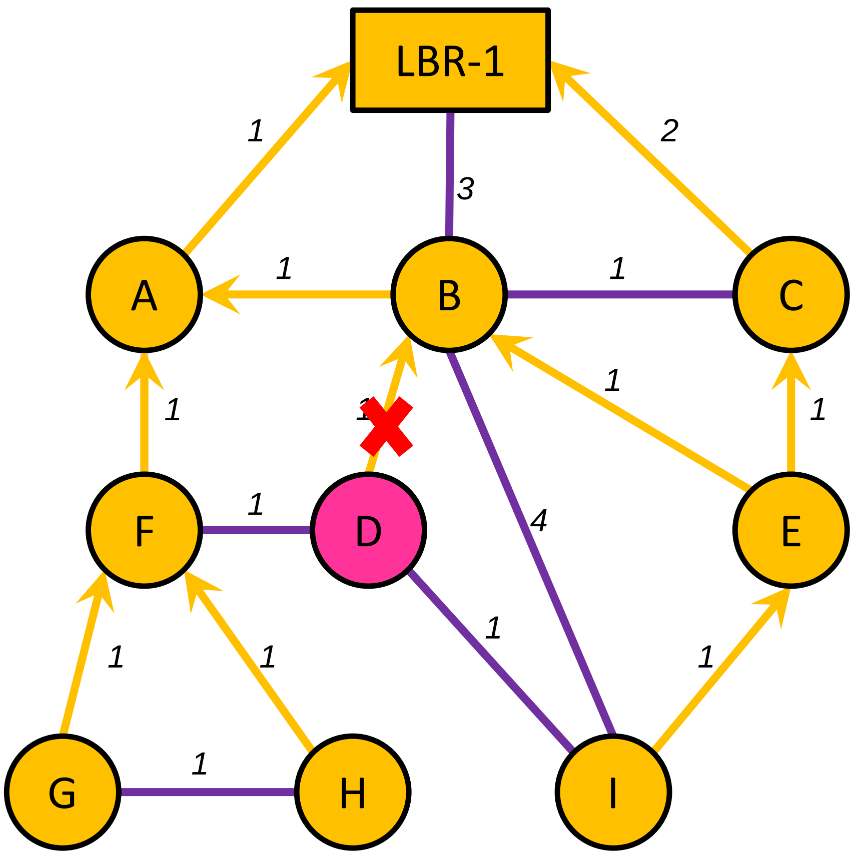
- Suppose a link A—F becomes viable
- Node A multicasts an RA-DIO
- Node F sees a chance to rejoin grounded DAG at depth 2 through Node A
- Node F starts a DAG Hop timer of duration α 1 associated with Node A

DAG Maintenance (7/10)



- Node F's DAG Hop Timer expires
- Node F joins to the grounded DAG at depth 2 by adding A as a DAG parent, and removing D
- Node F multicasts an RA-DIO
- Nodes G and H follow Node F to the grounded DAG

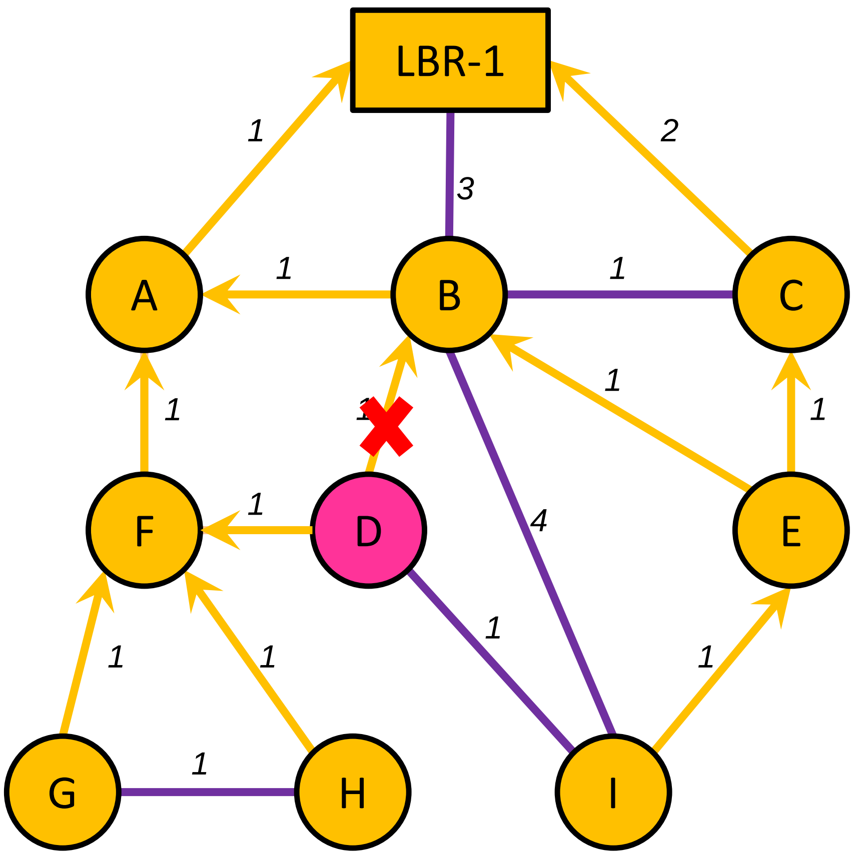
DAG Maintenance (8/10)



- Node D sees a chance to rejoin DAG LBR-1 at depth 3 through Node F

- Node D starts a DAG Hop timer of duration α 2 associated with Node F, in addition the DAG Hop timer already running with duration α 4 associated with Node I

DAG Maintenance (9/10)



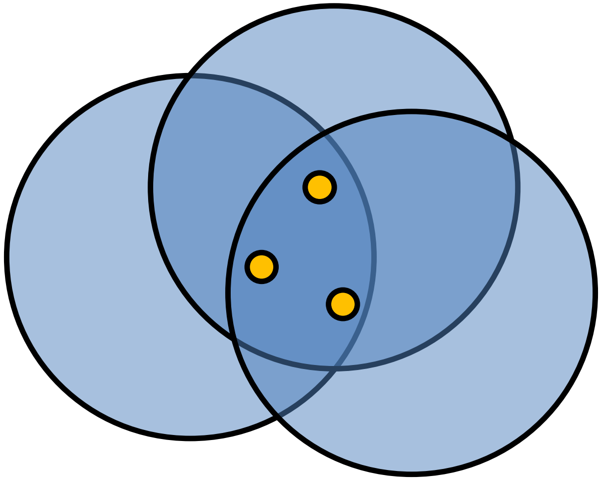
- Node D's DAG Hop timer of duration α 2 tends to expire first
- Node D joins the grounded DAG at depth 3 by adding Node F as a DAG Parent
- The breaking-off and re-joining of the broken sub-DAG is thus coordinated with loop avoidance

DAG Maintenance (10/10)

- Loop Avoidance
  - Two mechanisms to avoid count-to-infinity
  - Floating DAG
    - Leave DAG, color sub-DAG, then look for new routes
    - Operation local to nodes that must increase their depth
    - Does not guarantee loop freedom
  - Sequence number change
    - Loop freedom, but expensive network-wide operation
    - Used infrequently if possible

Trickle Algorithm

- Concerns
  - Broadcast is expensive
  - Wireless channel is a shared, spatial resource
- Idea
  - Dynamic adjustment of transmission period
  - Suppress transmissions that may be redundant



- Parameters:
  - T_min: Minimum advertisement period
  - T_max: Maximum advertisement period
  - k: Suppression threshold
- Period adjustment:
  - On receiving *inconsistent* route information, reset to T_min
  - Otherwise, double up to T_max
- Suppression:
  - Increment count (c) when receiving *similar* advertisement
  - At end of period, transmit if $c < k$, set $c = 0$
- Proposal:
  - Carry T_min, T_max, and k in RA-DIO

Thanks!

Figures and slide materials are taken from the following sources:

1. https://tools.ietf.org/agenda/75/slides/roll-1.ppt

Main Five Criteria

- Table Scalability: how does the routing table size scale?
- Loss Response: how expensive is it when links come & go?
- Control Cost: how does the control overhead scale?
- Link Cost: can the protocol consider link properties?
- Node Cost: can the protocol consider node properties?