Last time

- Intra-domain routing won’t work on the Internet
  - DV and LS do not scale
  - How do we pick a “global” metric?

- We talked about inter-domain routing
  - Mechanism and policy
  - BGP: Use path vector algorithm instead of DV or LS
  - Path vector looks at reachability info only
    » Ignores metrics
    » Route selection is based on local policy
Today: Multicast routing

- Multicast service model
- Host interface
- Host-router interactions (IGMP)
- Multicast Routing
  - Distance Vector
  - Link State
  - Shared tree
- Limiters
  - Deployment issues
  - Inter-domain routing
  - Operational/Economic issues
Motivation

- Efficient delivery to multiple destinations (e.g. video broadcast)

- Network-layer support for one-to-many addressing
  - Publish/subscribe communications model
  - Don’t need to know destinations
IP Multicast service model

- Communications based on groups
  - Special IP addresses (Class D in IPv4) represent “multicast groups”
  - Anyone can join group to receive packets
  - Anyone can send to group
    - Sender need not be part of group
  - Dynamic group membership – can join and leave at will

- Unreliable datagram service
  - Extension to unicast IP
  - Group membership not visible to hosts
  - No synchronization

- Explicit *scoping* to limit spread of packets
Elements of IP Multicast

1. **Host interface**
   - Application visible multicast API
   - Multicast addressing
   - Link-layer mapping

2. **Host-Router interface**
   - IGMP

3. **Router-Router interface**
   - Multicast routing protocols
(1) Host interface

- Senders (not much new)
  - Set TTL on multicast packets to limit “scope”
    » Scope can be administratively limited on per-group basis
  - Send packets to *multicast address*, represents a group
  - Unreliable transport (no acknowledgements)

- Receivers (two new interfaces)
  - Join multicast group (group address)
  - Leave multicast group (group address)
  - Typically implemented as a socket option in most networking API
Multicast addressing

- Special address range:
  - Class D (3 MSBs set to 1) 224.0.01- 239.255.255.255
  - Reserved by IANA for multicast

- Which address to use for a new group?
  - No standard
  - Global random selection
  - Per-domain addressing

- Which address to use to join an existing group?
  - No standard
  - Separate address distribution protocol (may use multicast)
Link-layer multicast

- Many link-layers protocols have multicast capability
  - Ethernet, FDDI

- Translate IP Multicast address into LL address
  - E.g. Map 28 bits of IP Multicast address in 23bit Ethernet Multicast addresses
  - Senders send and receive on link-layer Multicast addresses
  - Routers must listen on all possible link-layer Multicast addresses

- Not an issue for point-to-point links
Internet Group Management Protocol (IGMP)

- (2) Host-router interface
- Goal: Communicate group membership between hosts and routers

- Soft-state protocol
  - Hosts explicitly inform their router about membership
  - Must periodically refresh membership report
  - Routers implicitly timeout groups that aren’t refreshed
  - Why isn’t explicit “leave group” message sufficient?

- Implemented in most of today’s routers and switches
How IGMP works (roughly)

- Router broadcasts *membership query* to 224.0.01 (all-systems group) with TTL=1
- Hosts start random timer (0-10 sec) for each group they have joined

- When a host’s timer expires for group G, send *membership report* to group G, with TTL=1
- When a member of G hears a report, they reset their timer for G
- Router times out groups that are not “refreshed” by some host’s report
Multicast routing

- (3) Router-router interface

- Goal: Build distribution tree for multicast packets
  - Efficient tree (ideally, shortest path)
  - Low join/leave latency

- Several approaches
  - Distance Vector/Link State
    » Leverage existing unicast routing protocols
  - Shared tree
    » Unicast/multicast hybrids
**Multicast routing taxonomy**

- **Source-based tree**
  - *Separate shortest path tree for each source*
  - *Flood and prune* (DVMRP, PIM-DM)
    - Send multicast traffic everywhere
    - Prune edges that are not actively subscribed to group
  - *Link-state* (MOSPF)
    - Routers flood groups they would like to receive
    - Compute shortest-path trees on demand

- **Shared tree** (PIM-SM)
  - *Single distributed tree shared among all sources*
  - Specify rendezvous point (RP) for group
  - Senders send packets to RP, receivers join at RP
  - RP multicasts to receivers; Fix-up tree for optimization
Source-based vs Shared

**Source-based tree**
- Efficient trees; low delay, even load
- Per-source state in routers (S,G)

**Shared-tree**
- Higher delay, skewed load
- Per-group state only (G)
Source-based: Flood and Prune (DV)

- Extensions to unicast distance vector algorithm
- Goal
  - Multicast packets delivered along shortest-path tree from sender to members of the multicast group
  - Likely have different tree for different senders
- Distance Vector Multicast Routing Protocol (DVMRP) developed as a progression of algorithms
  - Reverse Path Flooding (RPF)
  - Reverse Path Broadcast (RPB)
  - Reverse Path Multicast (RPM)
Source-based: Reverse Path Flooding (RPF)

- **Observation:** Shortest-path multicast tree is subtree of shortest-path broadcast tree
- **Approach:** Use shortest-path broadcast tree
- **Use reverse path** to determine shortest path
  - Router forwards a packet from $S$ iff received from the shortest-path link to $S$
  - Exactly what is in entry in forwarding table?
    - To reach $S$ along shortest path, use link $L$
    - If received packet from $S$ on $L$, it came along shortest path
- **How are packets forwarded?**
  - **Flooding** – forward packets to multicast address out to all links except incoming link (hence reverse path flooding)
Example: Reverse Path Flooding

Forward packets on shortest path from X to S

Problem: Flooding causes duplicate packets to be sent on LANs
Solution: Reverse Path Broadcast (RPB)

- Flooding vs. broadcast
  - With flooding, a single packet can be sent along an individual link multiple times
    - Each router attached to link can potentially forward same packet
  - RPB sends a packet along a link at most once
- Approach: Define parent and child routers for each link
  - Relative to each link and each source S
  - Router is a parent for link if it has minimum path to S
  - All other routers on the link are children
  - Only parent router is allowed to forward multicast packets on link
- How to decide parent and children routers for link?
  - In routing updates; router determines if is parent
Example:
Reverse Path Broadcasting

B not parent for S
Don’t forward
Source-based: Reverse Path Multicast (RPM)

- Problem: Still broadcasting up to leaf networks
- Idea: Instead of actively building tree, use reports to actively prune tree
- Start with a full broadcast tree to all links (RPB),
- Prune (S,G) at leaf if it has no members
  - Send Non-Membership Report (NMR) to prev-hop for S
- If all children of router R prune (S,G)
  - Send NMR for (S,G) to parent of R
- Soft-state management (must refresh NMR or rejoin)
- New group member sends graft (anti-prune) message
Source-based: Link State

- Use existing link-state routing algorithm (e.g. OSPF)
- Idea: Include active groups in LSPs
  - Each router can compute shortest path tree from source to all destinations for any group
  - Trigger new flood of LSPs on group membership change

- Performance issues
  - Expensive to precompute all (S,G) trees
  - Keep cache of trees and compute new trees on demand when new (S,G) packet arrives
  - Workload/topology dependent

- Best known example: MOSPF
Shared tree approaches

- Unicast packets to Rendezvous Point (RP), which multicasts packet on shared tree
- Tree construction
  - Receivers send join messages to RP for each group
  - Intermediate routers install state to create per-group tree
  - Key advantage is routers only store O(G) state
  - Potential optimizations: reroute to source-specific trees for local group members or high data-rate sources
  - Example: PIM-SM
- Issues
  - Delay, fault tolerance, RP selection
IP Multicast today

- IP Multicast has generated 1000s of papers, but has not been widely deployed in the Internet...

- Why?
  - General deployment difficulties
    » Most routers don’t support multicast
    » Mbone (multicast backbone)
  - Inter-domain multicast complexity
    » Policy issues again
  - Economics of multi-source multicast
    » What/who do you charge for multicast traffic?
Multicast evolution

- How to deploy a new network-layer service?
  - Difficult to change router software
  - Difficult to change all routers

- Mbone (tunneling)
  - Special multicast routers (built from PCs/Workstations)
  - Construct virtual topology between them (overlay)
  - Run routing protocol over virtual topology
  - Virtual point-to-point links called **tunnels**
    » Multicast traffic encapsulated in IP datagrams
    » Multicast routers forward over tunnels according to computed virtual next-hop
Tunneling

Encapsulation

132.239.4.6

De-encapsulation

128.2.1.2

IP Header
dst=128.2.1.2

IP Header
dst=224.x.x.x

Data

Data

IP Header
dst=224.x.x.x

IP Header
dst=224.x.x.x
Virtual overlay network

Real topology with tunnels

Virtual overlay topology
Mbone Pro/Con

- **Success story**
  - Multicast video to 20 sites in 1992
  - Easy to deploy, no explicit router support
  - Ran DVMRP and had 100s of routers

- **Drawbacks**
  - Manual tunnel creation/maintenance
  - Inefficient
  - No routing policy (single tree)
  - Why would an ISP deploy a new Mbone node?
Inter-domain Multicast routing

- Technical issues
  - How to exchange reachability information?
  - How to construct trees?
  - Who controls RP in shared tree?
- MBGP (Multicast BGP): reachability to multicast sources per prefix
- PIM-SM: shared tree multicast protocol
- MSDP (Multicast source discovery protocol): RP per group per AS, communication presence of group sources between RPs
- BGMP (Border gateway multicast protocol): alternative proposal, single shared tree with group addresses owned by individual ASs
Economic issues

- ISP router migration cycle
  - Can’t afford new routers on edge
- Domain independence
  - Do I want my customers multicast controlled by an RP in a competitors domain?
  - Why run an RP for which I have no senders or receivers?
- Billing model
  - Inconsistent with input-rate-based billing
  - No group management (how big is group?)
- Group management
  - Who is in the group? Who can send? Security…
- Limited Multicast addresses
Summary

- Multicast service model
  - One-to-many, anonymous communication
  - Simple host interface
- Per-source tree routing
  - Efficient trees
  - $O(S^*G)$ state explosion for large networks/groups
- Shared tree
  - More complex, fragile, hard to manage
  - Inefficient trees
  - Only requires $O(G)$ state on routers
- Operational and Economic issues matter in deployment
- Killer app not found
Next time

- Router design
  - How routers are actually built