Multicast routing principles in Internet

Motivation

Recap on graphs

Principles

Multicast capability has been and is under intensive development in the 1990's

- MBONE used to multicast IETF meetings from 1992
- Extends LAN broadcast capability to WAN in an efficient manner
- Valuable applications
  - resource discovery
  - network load minimization by replacing many pt-to-pt transmissions
  - multimedia conferencing

Multicast addresses

32 bits

MSB(t)	network	host	Class
1110	**28 bits - multicast group address**		**D**
1111	**experiments**		**E**

224.0.0.0 - 239.255.255.255

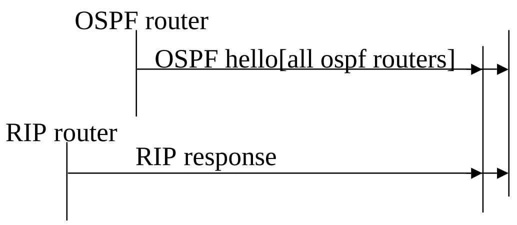
224.0.0.1	All systems
224.0.0.2	All routers
224.0.0.4	All DVMRP routers
224.0.0.1 - 224.0.0.255	Local segment usage only
239.0.0.0 - 239.255.255.255	Admin scoped multicast (local signifigance)
239.192.0.0 - 239.195.255.255	Organisation local scope

Ethernet MAC address: MACprefix+G --> no lookup, no ARP

Note: + Sender does not need to belong to G.

+ Address space is flat!

Resource discovery by MC simplifies network management

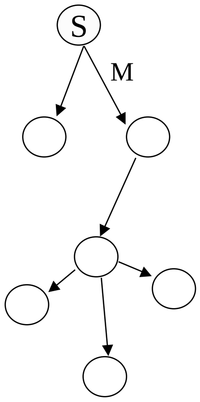


- No need for lists of neighbors, just use std MC address
- How to find corporate DNS -server --> MC to all nodes in corporate network.
- Network is easily flooded with messages.
- TTL can be used for Broadcast scope limitation
  - --> find nearest DNS or whatever
  - -- when TTL=0, router does not return ICMP msg!

Conferencing requirements include

- Multiple sources, multiple recipients, multiple media
- Variable membership
- Small conferences with intelligent media control (what is sent to where)
- Large conferences require media processing in special devices

Multipoint sessions differ from point-to-point communication

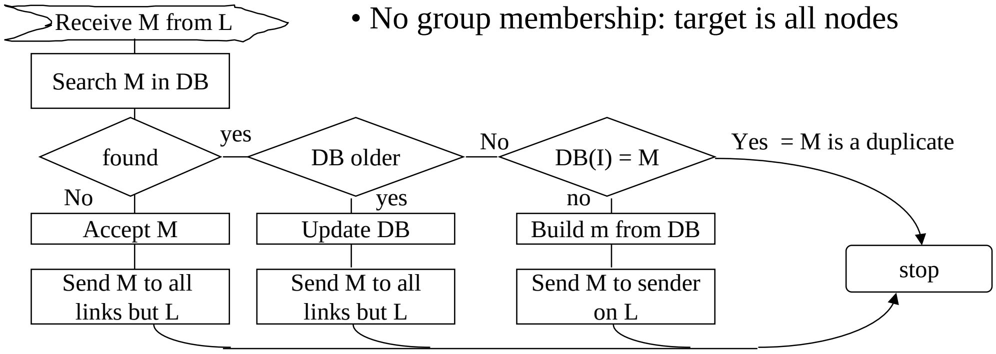


- Participants may join and leave the session.
- Receiver-makes good principle instead of session parameter negotiation.
- Window based flow control does not apply:
  -- use UDP / connectionless protocols

Flooding is the simplest MC algorithm

Flooding algorithm is

- Need to keep state (DB) in nodes!
- No group membership: target is all nodes



- Examples: OSPF, usenet news...

Alternative to DB in flooding is trace info in the message

- Trace info in Message lists all passed nodes
- Avoids a costly DB reads but may accept same M several times.
- If neighbor is in trace, does not send

Flooding guarantees that node will not forward the same packet twice. It does not guarantee that node will receive same packet only once! --> Greedy algorithm.
+++Does not depend on routing tables -->robust

Networks are modeled as Graphs.

G = (V, E),

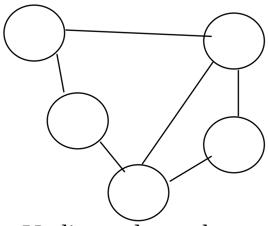
V - set of **vertices or nodes** (non-empty, finite set)

E = {e_j | j = 1, 2, … M} - set of **edges or links.**

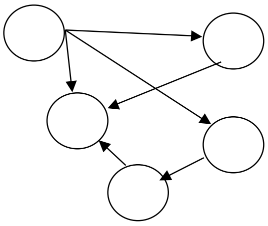
$$e_j = (v_i, v_k) = (i, k)$$

Nodes i and k are **adjacent** if link (i, k) exists.
Nodes i and k are also called **neighbors**.

Links are bi-, arcs are unidirectional



Undirected grapth

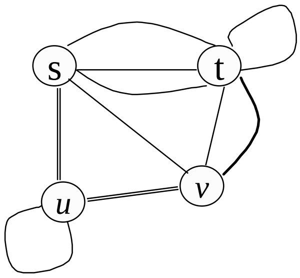


Directed graph

Degree of a node is the number of its neighbors or the number of links **incident on the node**.

Unidirectional links,
$a_j = (v_i, v_k) = [i,k]$ are called **arcs**.
If links and nodes have properties, the graph is called a **network**.

Graphs with parallel links are called multigraphs



Links between a node and itself are **self loops**.

Graph with no parallel links and no self loops is a **simple graph**.

A **path** in a network is a sequence of links beginning at some node s and ending at some node t. = **s,t-path**. If s = t, path is called a **cycle**. If an intermediate node appears no more than once, it is a **simple cycle**.

Graph is **Connected** if there is at least one path between every pair of nodes.

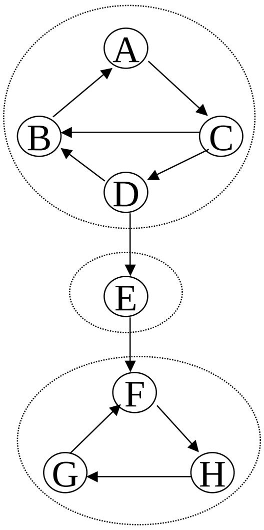
- A subset of nodes with paths to one another is a connected component.

Reflective: By def. $\exists\ i,i$-path
Symmetric: $\exists\ i,j$-path $\Rightarrow \exists\ j,i$-path
Transitive: $\exists\ i,j$-path and $\exists\ j,k$-path $\Rightarrow \exists\ i,k$-path

$\Rightarrow$ Components are equivalence classes and the component structure is a partition of the graph.

Partition applies to links and nodes alike.

A directed graph is **strongly connected** if there is a **directed path** from every node to every other node.



- Directed connectivity is not symmetric.
- A subset of nodes with directed paths from any one node to any other is a **strongly connected component**.
- A node belongs to exactly one strongly connected c. An arc is part of *at most one* strongly connected c.

A **tree** is a graph without cycles

- Given a Graph $G = (V, E)$, H is a subgraph of G if $H = (V', E')$ where $V' \subset V$ and $E' \subset E$
- A **spanning tree** is a connected graph without cycles.
- If graph is not necessarily connected, we talk about **a forest**.

Spanning trees model minimally connected networks

- ST is a minimum cost network.
- Only a single path exists between any two nodes in a ST --> routing is trivial.
- If a graph has *N* nodes, any tree spanning the nodes has exactly *N* - 1 edges.
- Any forest with *k* components has exactly *N* - *k* edges. (proof by induction starting from graph with no edges).

A set of edges whose removal disconnects a graph is called a **disconnecting set.**

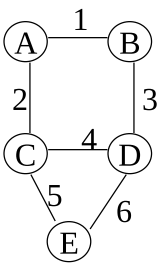
- **XY-cutset** partitions a graph to subgraphs X and Y.
- In a tree any edge is **a minimal cutset**.
- A minimal set of nodes whose removal partitions the remaining nodes into two connected subgraphs is called **a cut**.

Suomalaiset graafitermit

Vertex, node - kärki,solmu
Edge, link - syrjä, linkki, sivu, kaari, haara
Adjacent - viereinen
Neighbor - naapuri
Degree of a node - solmun aste(?)
Arc - kaari
Cycle, Loop - silmukka
Path - polku
Directed path - suunnattu polku
Connected - yhteydellinen, yhdistetty
Strongly connected - vahvasti yhteydellinen

Subgraph - aligraafi
Tree - puu
Spanning tree - virittäjäpuu
Forest - metsä
Disconnecting set - erotusjoukko
Cut - leikkaus
XY-cutset - XY-leikkaus-joukko

Adjacency and Incidence Matrices are used to present Graphs



Adjacency Matrix (Node × Node)

Node	A	B	C	D	E
A	0	1	1	0	0
B	1	0	0	1	0
C	1	0	0	1	1
D	0	1	1	0	1
E	0	0	1	1	0

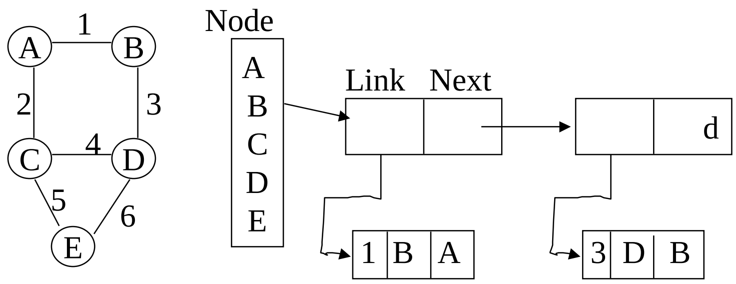
Incidence Matrix (Node × Link)

Node	1	2	3	4	5	6
A	1	1	0	0	0	0
B	1	0	1	0	0	0
C	0	1	0	1	1	0
D	0	0	1	1	0	1
E	0	0	0	0	1	1

For an undirected graph Adjacency matrix is symmetric.

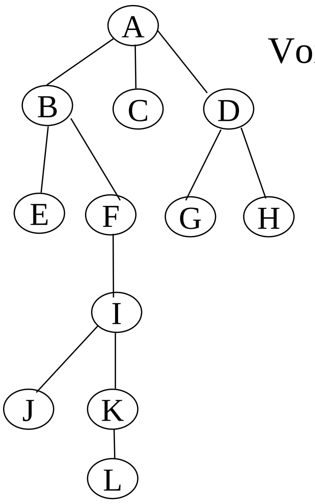
For directed graphs +1 is source and -1 is sink of an arc

For graph algorithms linked list presentation of adjacency is convenient



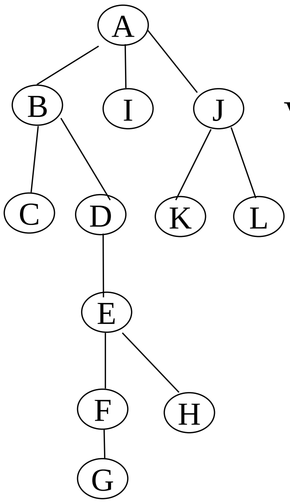
A Tree can be traversed by Breadth-first-search

Works for directed links




```
Void <- BfsTree( n, root, n_adj_list )
    dcl n_adj_list [n, list]  /* array of lists of neighbors
        scan_queue [queue]
    InitializeQueue( scan_queue)
    Enqueue(root, scan_queue)
    while NotEmpty(scan_queue)
        node <- Dequeue(scan_queue)
        Visit (node)
        for each (neighbor, n_adj_list[node])
            Enqueue(neighbor, scan_queue)
```

A Tree can also be traversed by Depth-first-search



Works for directed links

```
Void <- DfsTree( n, root, n_adj_list )
    dcl n_adj_list [n, list]

    Visit (root)
    for each (neighbor, n_adj_list[node])
        DfsTree(n, neighbor, n_adj_list)
```


An undirected graph can be traversed by Depth-first-search

```
Void <- Dfs ( n, root, n_adj_list )
    dcl n_adj_list [n, list]
        visited[n]          /* keeps track of progress
    void <- DfsLoop(node)
        if not visited[node]
            visited[node] <- TRUE
            Visit (node)
            for each (neighbor, n_adj_list[node])
                DfsLoop(neighbor)
    visited <- FALSE
    DfsLoop( root )
```

We can now find and label the connected components of an arbitrary graph

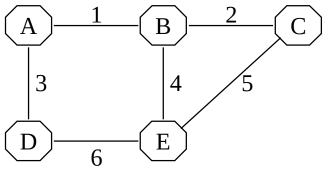
```
Void <- LabelComponents(n, n_adj_list)
    dcl n_component_nr[n], n_adj_list[n, list]
    void <- Visit(node)
        n_component_nr[node] <- ncomponents
    n_component_nr <-   0
    ncomponents <-  0
    for each ( node, nodeset )
        if  (n_component_nr[node] = 0
            ncomponents +=1
            Dfs( node, n_adj_list )
```

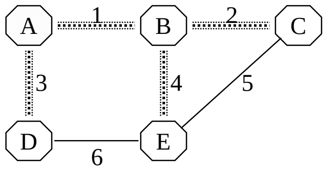

Minimum Spanning Tree is the ST with minimum cost

- We assign a length to each edge of the graph. “Length” can be distance, cost, a measure of delay or reliability.
- We look for minimum total length/cost, thus we talk about MST.
- If the graph is not connected, we may look for a minimum spanning forest.

$n = c + e$, where n is the number of nodes, c the number of components and e number of edges selected so far holds always.

MC to a *spanning tree* leads to reception only once in each node





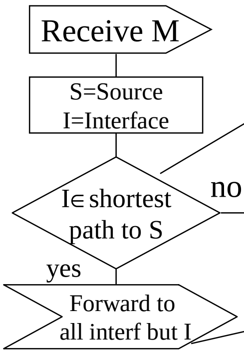
- Requires on/off bit (∈ ST) per link
- No group membership
- Concentrates traffic to the STlinks
- Ideal would be a tree that
  - spans the group members only
  - minimizes state information in nodes
  - optimizes routes based on metrics

A Greedy MST algorithm

```
List <- Greedy( properties )
   dcl properties [list, list],
        candidate_set[list], solution[list]

   void <- GreedyLoop( *candidate_set, *solution)
      dcl test_set[list], candidate_set[list], solution[list]

      element <- BestElementOf(candidate_set)   /* for MST: shortest edge
      test_set <- element ∪ solution
      If test_set is feasible                        /* for MST: no cycles
         solution <- test_set
      candidate_set <- candidate_set \ element
      If candidate set is not Empty
         Greedy_Loop( *candidate_set, *solution)

solution <- ∅
If (candidate_set <- ElementsOf(properties)) is not Empty
   GreedyLoop( *candidate_set, *solution)
return(solution)
```

Reverse-Path Forwarding computes an implicit spanning tree per source, is OK for dense trees

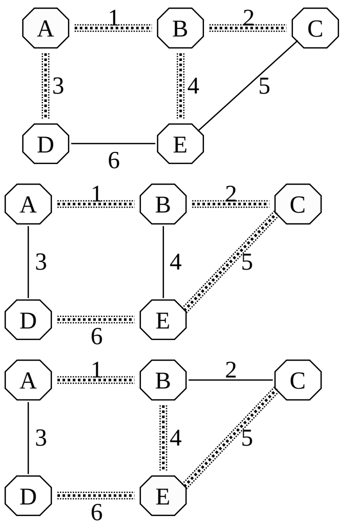
• RPF was first used in MBone



Note: path is computed from S to node.
In symmetric networks = path from node to S

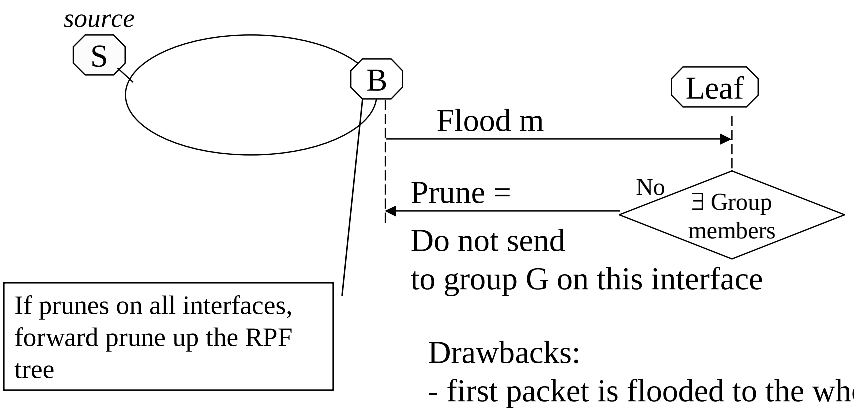
Looking one step further: send only if our Node is on shortest path from S to next Node.
Requires 1 bit/source and /link in link state DB

Reverse path forwarding properties



- No group membership but can be scoped by TTL
- Guarantees fastest possible delivery since uses shortest paths only
- Different tree for each source --> traffic is spread over multiple links leading to better network utilization

“Flood and prune” introduces dynamic group membership



Drawbacks:
- first packet is flooded to the whole net
- nodes must keep state per S and G.
- state is transient (timed out)

Steiner tree spans the group with the minimal cost according to link metrics

- Has never actually been used, only simulated:
  - Finding the mimimum Steiner tree in a graph has exponential complexity and result is not necessarily optimal
  - The tree is undirected: links must be symmetrical
  - Algorithm is monolithic, can’t be distributed
  - The tree is unstable when changes occur: traffic routes change dramatically when e.g a member leaves.
- Popular because of its mathematical complexity
- Leads to Center based approach (CBT, PIM)