# Wireless Mesh Networks

COS 463: Wireless Networks
Lecture 6

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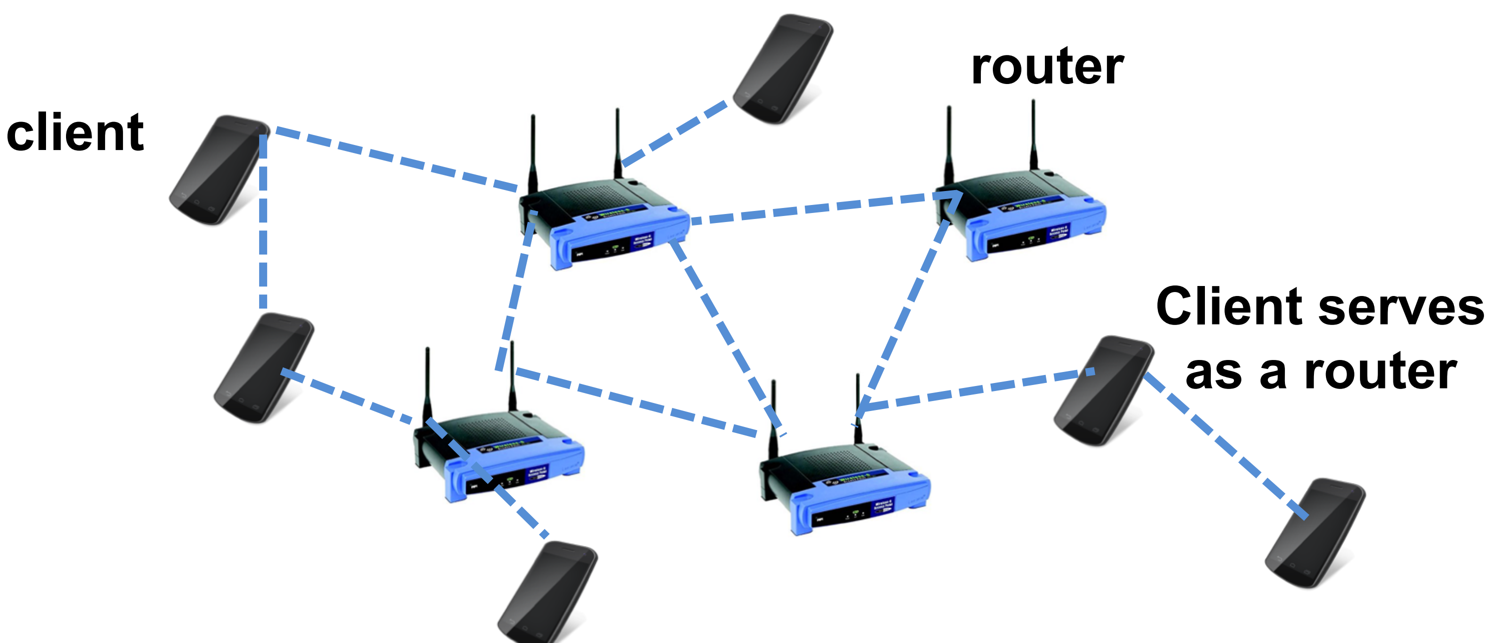
[Parts adapted from I. F. Akyildiz, B. Karp]

# Wireless Mesh Networks

- Describes wireless networks in which **each node can communicate directly with any other node**
- Traditional wireless network traffic goes through **APs**
- Mesh networks: **Remove this restriction**
  - **Multiple paths: Mesh**



# Distance Vector & Link State Routing

- Both assume each router knows single-hop routing information:
  - **Address of each neighbor**
  - **Cost of reaching each neighbor (metric)**
- **Distance Vector:** Router knows **just the metric** to each destination
- **Link State:** Router knows **entire network topology,** computes shortest path to each destination

# Today

1. **Distance Vector Routing**
   - **New node join**
   - Broken link
   - Route changes

1. Destination Sequenced Distance-Vector Routing (DSDV)

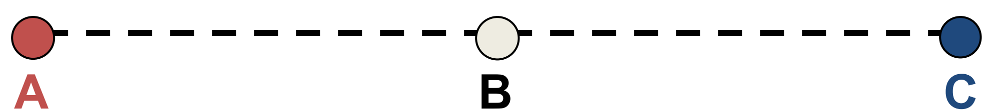
2. Dynamic Source Routing (DSR)

3. Roofnet

# Distance Vector Routing

- Every node maintains a **routing table**
  - For each **destination** in the mesh:
    - The **number of hops** to reach the destination (**metric**)
    - The **next** node on the path towards the destination

- All nodes **periodically, locally broadcast** their **routing table**
  - **Traffic overhead** due to broadcasting




A

| Dest. | Next | Metric |
|---|---|---|
| A | A | 0 |
| B | B | 1 |
| C | B | 2 |

B

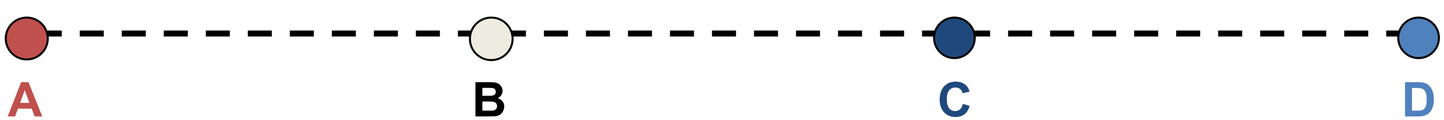
| Dest. | Next | Metric |
|---|---|---|
| A | A | 1 |
| B | B | 0 |
| C | C | 1 |

C

| Dest. | Next | Metric |
|---|---|---|
| A | B | 2 |
| B | B | 1 |
| C | C | 0 |

# Distance Vector – New Node Join

- **D** joins the network




| Dest. | Next | Metric |
|---|---|---|
| A | A | 0 |
| B | B | 1 |
| C | B | 2 |
| | | |

| Dest. | Next | Metric |
|---|---|---|
| A | A | 1 |
| B | B | 0 |
| C | C | 1 |
| | | |

| Dest. | Next | Metric |
|---|---|---|
| A | B | 2 |
| B | B | 1 |
| C | C | 0 |
| | | |

# Distance Vector – New Node Join

- D joins the network
- **D's** broadcast first **updates C's table** with new entry for **D**

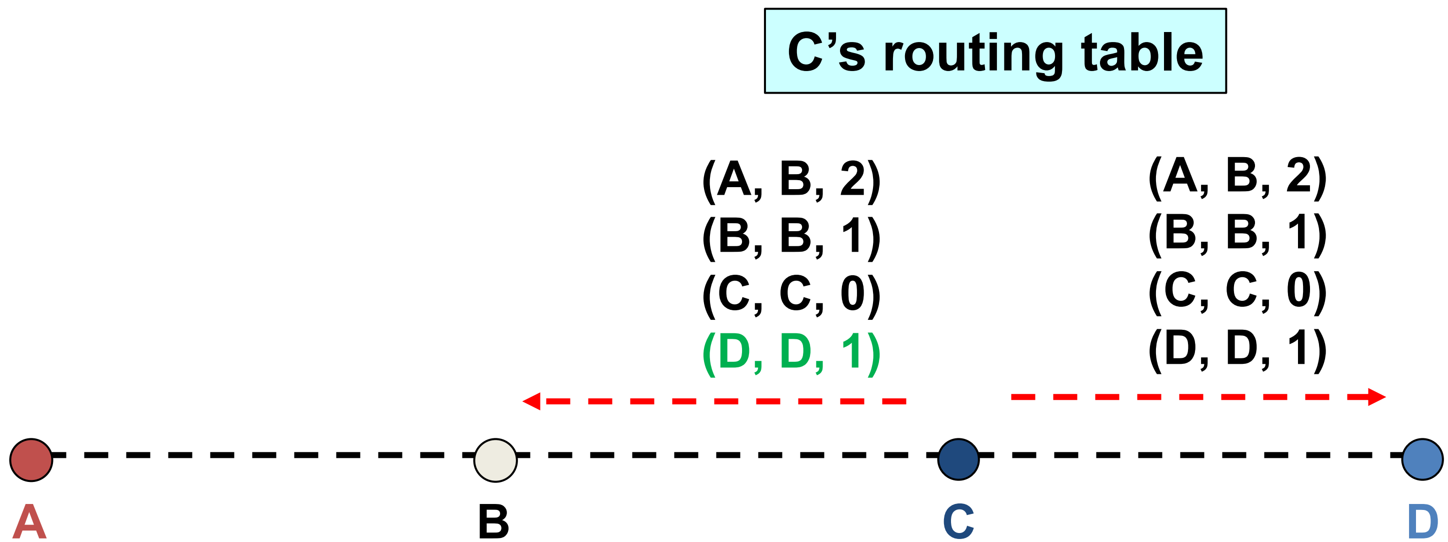

| Dest. | Next | Metric |
|---|---|---|
| A | A | 0 |
| B | B | 1 |
| C | B | 2 |
| | | |

| Dest. | Next | Metric |
|---|---|---|
| A | A | 1 |
| B | B | 0 |
| C | C | 1 |
| | | |

| Dest. | Next | Metric |
|---|---|---|
| A | B | 2 |
| B | B | 1 |
| C | C | 0 |
| D | D | 1 |

# Distance Vector – New Node Join

- Now **C** broadcasts its routing table
  - **B and D hear** and **add new entries, incrementing metric (hops)**




**A**

| Dest. | Next | Metric |
|---|---|---|
| A | A | 0 |
| B | B | 1 |
| C | B | 2 |
| | | |

**B**

| Dest. | Next | Metric |
|---|---|---|
| A | A | 1 |
| B | B | 0 |
| C | C | 1 |
| D | C | 2 |

**C**

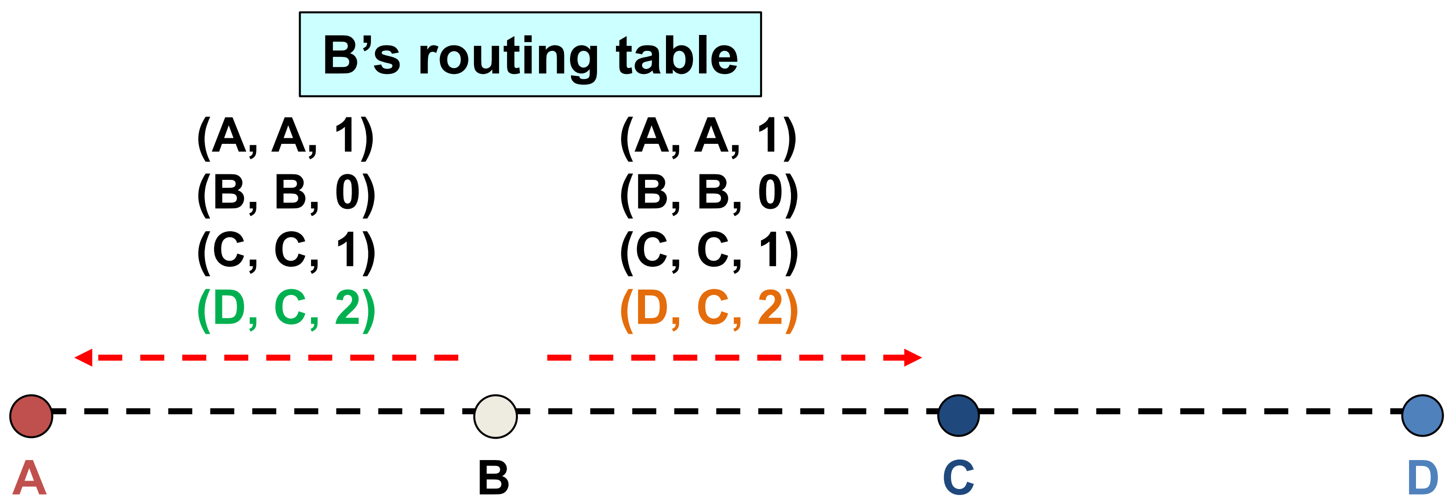
| Dest. | Next | Metric |
|---|---|---|
| A | B | 2 |
| B | B | 1 |
| C | C | 0 |
| D | D | 1 |

**D**

| Dest. | Next | Metric |
|---|---|---|
| A | C | 3 |
| B | C | 2 |
| C | C | 1 |
| D | D | 0 |

# Distance Vector – New Node Join

- Now **B** broadcasts its routing table
  - **A and C hear** and **add new entries, incrementing metric (hops)**




**A**

| Dest. | Next | Metric |
|---|---|---|
| A | A | 0 |
| B | B | 1 |
| C | B | 2 |
| D | B | 3 |

**B**

| Dest. | Next | Metric |
|---|---|---|
| A | A | 1 |
| B | B | 0 |
| C | C | 1 |
| D | C | 2 |

**C**

| Dest. | Next | Metric |
|---|---|---|
| A | B | 2 |
| B | B | 1 |
| C | C | 0 |
| D | D | 1 |

**D**

| Dest. | Next | Metric |
|---|---|---|
| A | C | 3 |
| B | C | 2 |
| C | C | 1 |
| D | D | 0 |

# Today

1. **Distance Vector Routing**
   – New node join
   – **Broken link**
   – Route changes

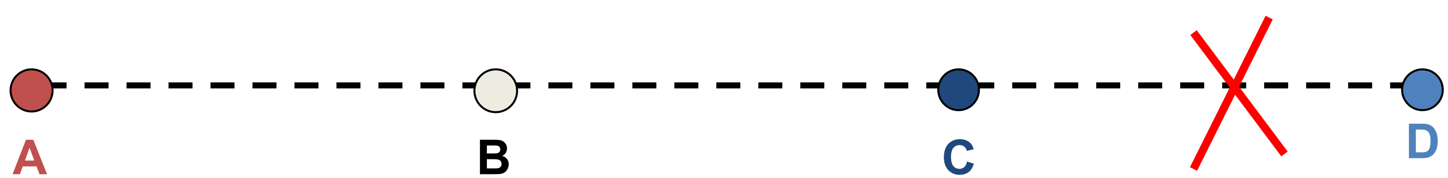
1. Destination Sequenced Distance-Vector Routing (DSDV)

2. Dynamic Source Routing (DSR)

3. Roofnet

# Distance Vector – Broken Link

- **Suppose link C ←→ D breaks**



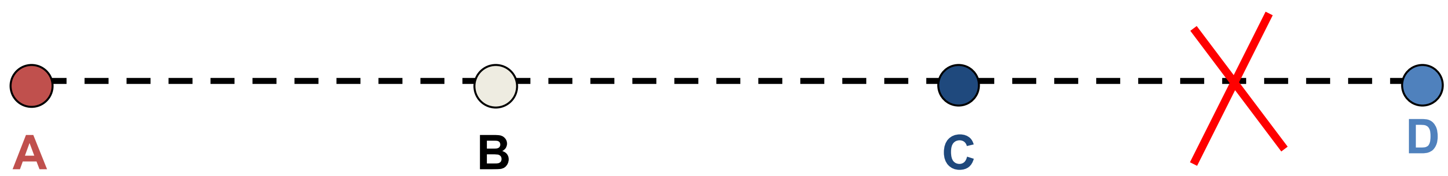

| Dest. | Next | Metric |
|---|---|---|
| … | … | … |
| D | B | 3 |

| Dest. | Next | Metric |
|---|---|---|
| … | … | … |
| D | C | 2 |

| Dest. | Next | Metric |
|---|---|---|
| … | … | … |
| D | D | 1 |

# Distance Vector – Broken Link

1. C **hears no advertisement** from **D** for a ***timeout period***
   – **C** sets **D's** metric to ∞




A

| Dest. | Next | Metric |
|---|---|---|
| ... | ... | ... |
| D | B | 3 |

B

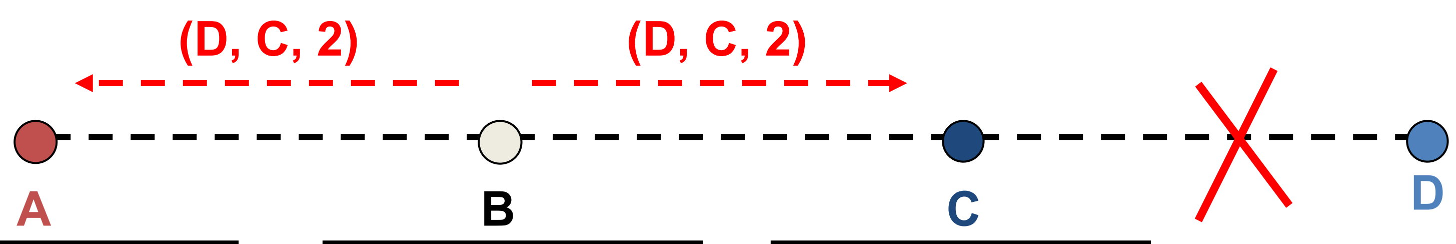
| Dest. | Next | Metric |
|---|---|---|
| ... | ... | ... |
| D | C | 2 |

C

| Dest. | Next | Metric |
|---|---|---|
| ... | ... | ... |
| D | D | ∞ |

# Distance Vector – Broken Link

1. **C** sets **D's** metric to ∞
2. **B** broadcasts its routing table
   – **C** **now accepts** **B's** entry for **D** **(3 < ∞)**



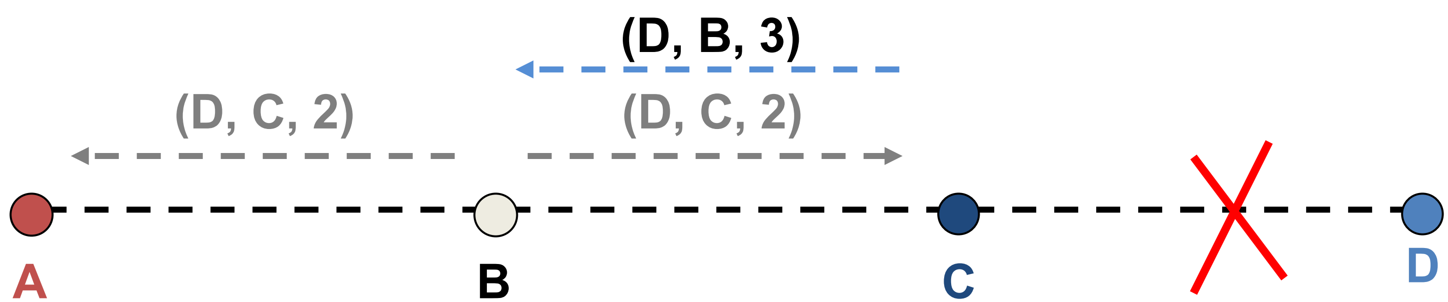

| Dest. | Next | Metric |
|---|---|---|
| … | … | … |
| D | B | 3 |

| Dest. | Next | Metric |
|---|---|---|
| … | … | … |
| D | C | 2 |

| Dest. | Next | Metric |
|---|---|---|
| … | … | … |
| D | B | 3 |

# Broken Link: Counting to Infinity

1. **C** sets **D's** metric to ∞
2. **B** broadcasts its routing table
3. **C** broadcasts its routing table
   – **B accepts C's new metric** (previous next-hop: **C**)



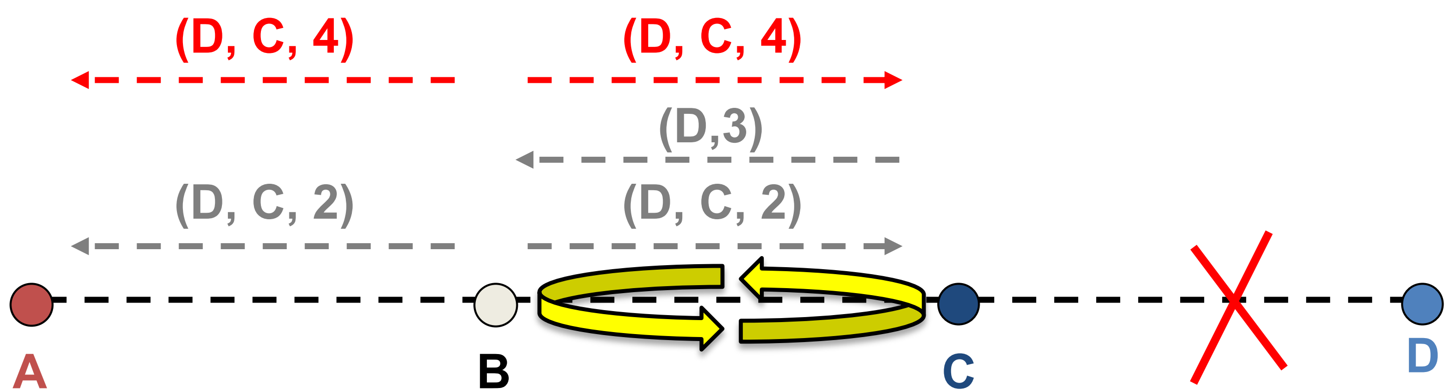

| Dest. | Next | Metric |
|---|---|---|
| … | … | … |
| D | B | 3 |

| Dest. | Next | Metric |
|---|---|---|
| … | … | … |
| D | C | 4 |

| Dest. | Next | Metric |
|---|---|---|
| … | … | … |
| D | B | 3 |

# Broken Link: Counting to Infinity

1. **C** sets **D's** metric to ∞
2. **B** broadcasts its routing table
3. **C** broadcasts its routing table
4. **B** broadcasts its routing table
   – **A, C** **accept** **B's** new metric (previous next-hops: **B**)




| Dest. | Next | Metric |
|---|---|---|
| … | … | … |
| D | B | 5 |

| Dest. | Next | Metric |
|---|---|---|
| … | … | … |
| D | C | 4 |

| Dest. | Next | Metric |
|---|---|---|
| … | … | … |
| D | B | 5 |

# Today

1. **Distance Vector Routing**
   – New node join
   – Broken link
   – **Route changes**

1. Destination Sequenced Distance-Vector Routing (DSDV)

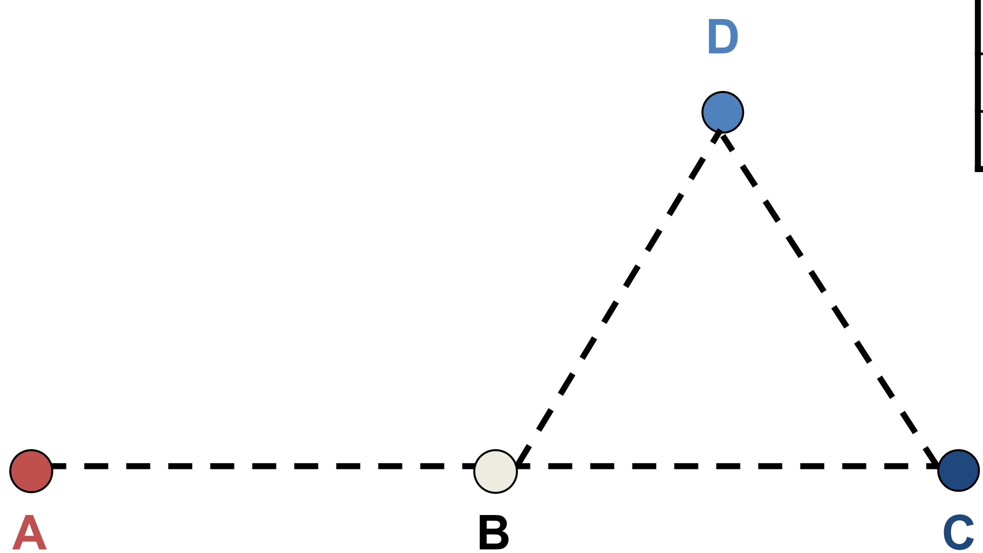
2. Dynamic Source Routing (DSR)

3. Roofnet

# Distance Vector – Route Change

- **D** moves to another place and broadcast its routing table

| Dest. | Next | Metric |
|---|---|---|
| A | C | 3 |
| B | C | 2 |
| C | C | 1 |
| D | D | 0 |




A

| Dest. | Next | Metric |
|---|---|---|
| A | A | 0 |
| B | B | 1 |
| C | B | 2 |
| D | B | 3 |

B

| Dest. | Next | Metric |
|---|---|---|
| A | A | 1 |
| B | B | 0 |
| C | C | 1 |
| D | C | 2 |

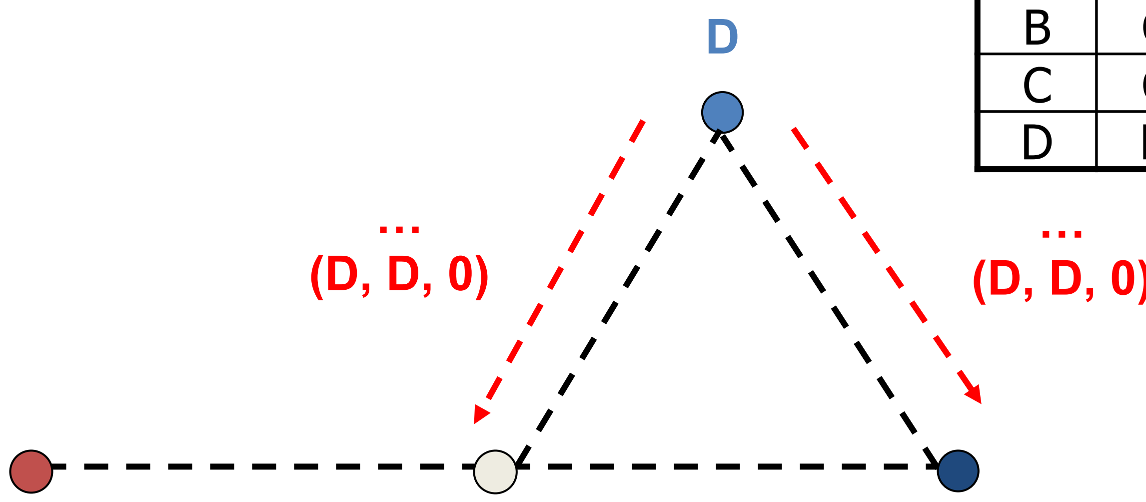
C

| Dest. | Next | Metric |
|---|---|---|
| A | B | 2 |
| B | B | 1 |
| C | C | 0 |
| D | D | 1 |

# Distance Vector – Route Change

- **D** moves to another place and broadcast its routing table

| Dest. | Next | Metric |
|---|---|---|
| A | C | 3 |
| B | C | 2 |
| C | C | 1 |
| D | D | 0 |




A

| Dest. | Next | Metric |
|---|---|---|
| A | A | 0 |
| B | B | 1 |
| C | B | 2 |
| D | B | 3 |

B

| Dest. | Next | Metric |
|---|---|---|
| A | A | 1 |
| B | B | 0 |
| C | C | 1 |
| D | D | 1 |

C

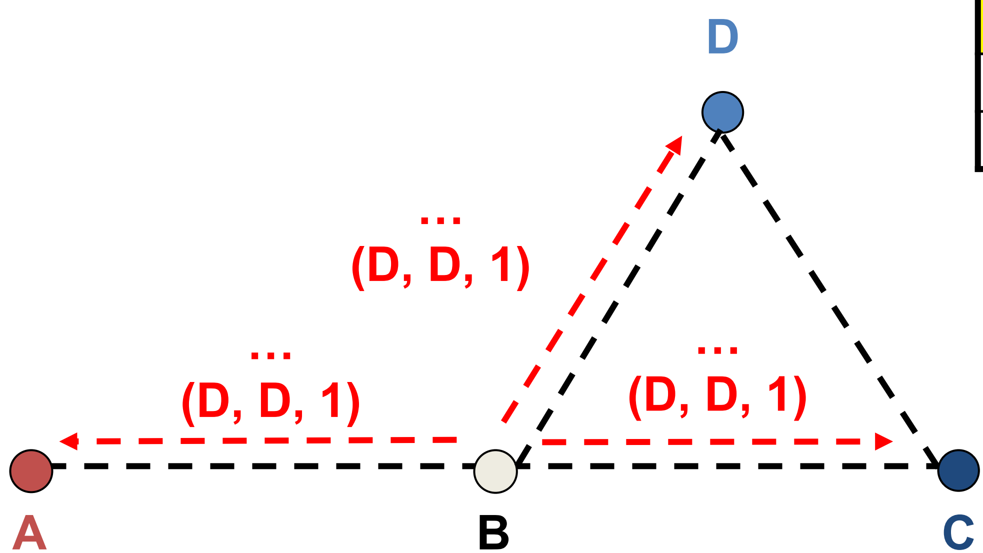
| Dest. | Next | Metric |
|---|---|---|
| A | B | 2 |
| B | B | 1 |
| C | C | 0 |
| D | D | 1 |

# Distance Vector – Route Change

- **D** moves to another place and broadcast its routing table
- **B** broadcast its routing table

D's table:

| Dest. | Next | Metric |
|---|---|---|
| A | B | 2 |
| B | B | 1 |
| C | C | 1 |
| D | D | 0 |




A's table:

| Dest. | Next | Metric |
|---|---|---|
| A | A | 0 |
| B | B | 1 |
| C | B | 2 |
| D | B | 2 |

B's table:

| Dest. | Next | Metric |
|---|---|---|
| A | A | 1 |
| B | B | 0 |
| C | C | 1 |
| D | D | 1 |

C's table:

| Dest. | Next | Metric |
|---|---|---|
| A | B | 2 |
| B | B | 1 |
| C | C | 0 |
| D | D | 1 |

# Today

1. Distance Vector Routing

2. **Destination Sequenced Distance-Vector Routing (DSDV)**
   - **New node join**
   - Broken link
   - Route advertisement

3. Dynamic Source Routing (DSR)

4. Roofnet

# Destination Sequenced Distance-Vector (DSDV) Routing

- Guarantees **loop freeness**

– **New routing table information:** ***Sequence number***

1. **Per-destination** information
2. **Originated** by destination
3. **Included** in routing advertisements

| Destination | Next | Metric | Seq. Nr |
|---|---|---|---|
| A | A | 0 | 550 |
| B | B | 1 | 102 |
| C | B | 3 | 588 |
| D | B | 4 | 312 |

# DSDV: Route Advertisement Rule

- **Rules to set sequence number:**

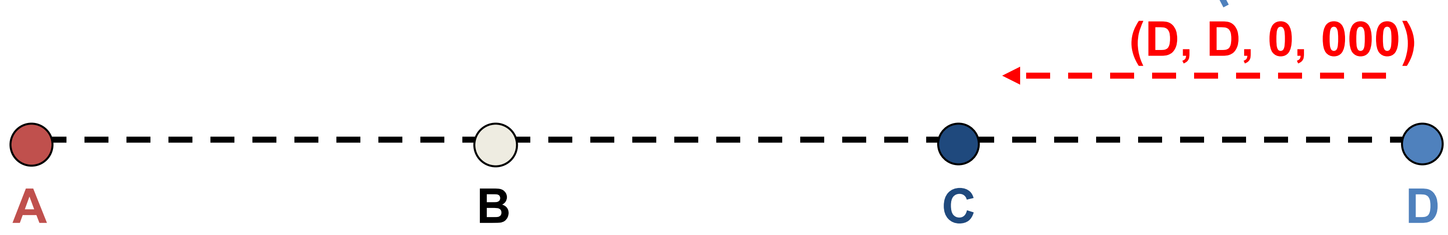
- Just before **node N**'s broadcast advertisement:
  - **Node N** sets:
    - **Seq(N) ← Seq(N) + 2**

- **Node N** thinks **neighbor P** is **no longer directly reachable**
  - **Node N** sets:
    - **Seq(P) ← Seq(P) + 1**
    - **Metric(P) ← ∞**

# DSDV – New Node

- D joins the network
- **D's** broadcast first **updates C's table** with new entry **for D**

**1. D broadcast for first time**
**Send Sequence number 000**




A:

| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | A | 0 | 550 |
| B | B | 1 | 104 |
| C | B | 2 | 590 |
| | | | |

B:

| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | A | 1 | 550 |
| B | B | 0 | 104 |
| C | C | 1 | 590 |
| | | | |

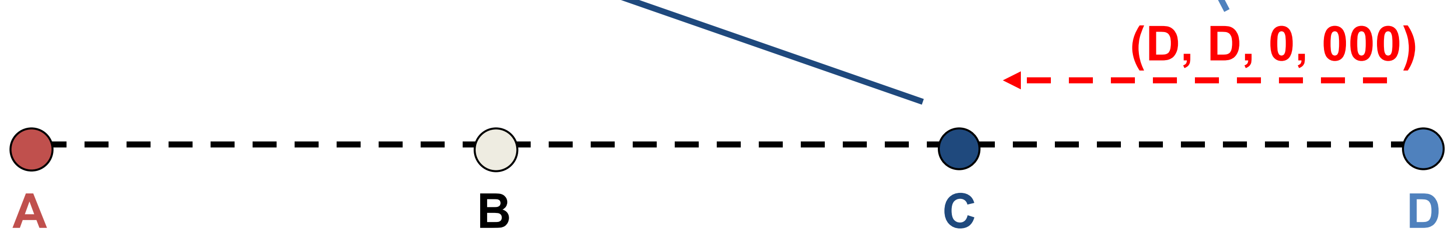
C:

| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | B | 2 | 550 |
| B | B | 1 | 104 |
| C | C | 0 | 590 |
| | | | |

# DSDV – New Node

2.1: Insert entry for D with same sequence number 000
2.2: Triggered broadcast of its own table

1. D broadcast for first time
Send Sequence number 000




**A**

| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | A | 0 | 550 |
| B | B | 1 | 104 |
| C | B | 2 | 590 |
| | | | |

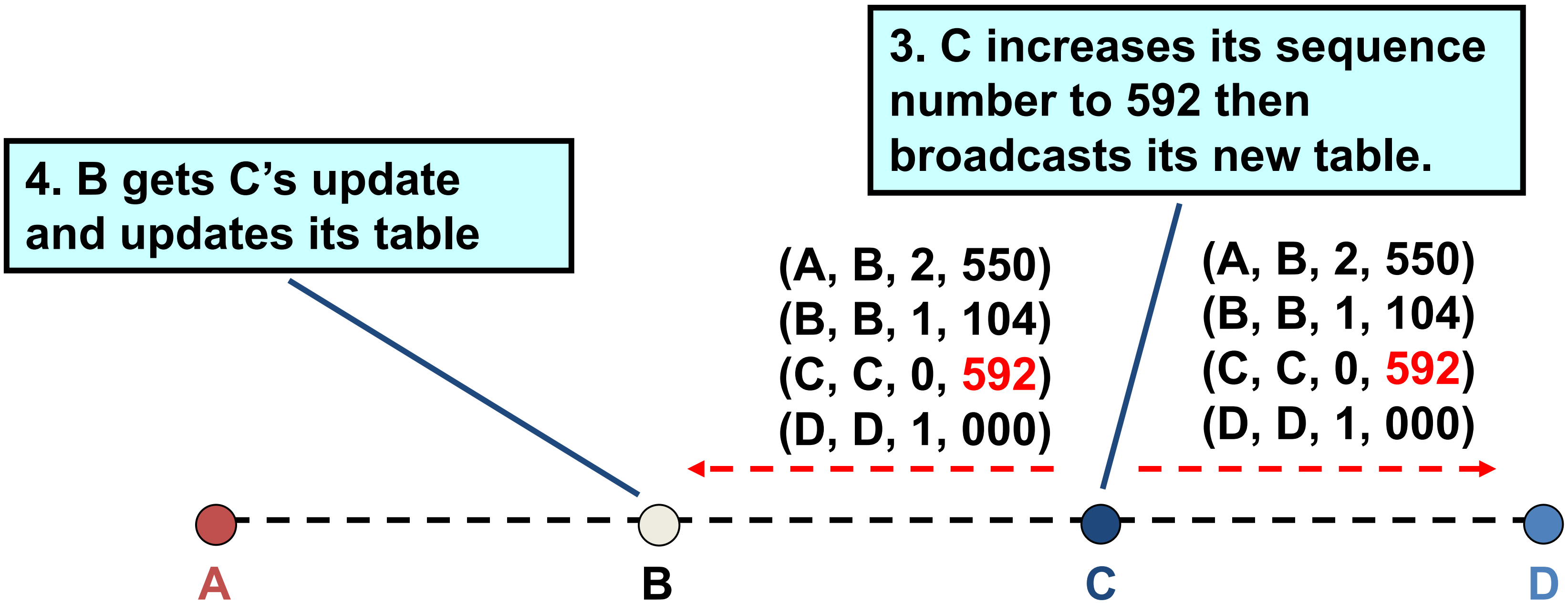
**B**

| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | A | 1 | 550 |
| B | B | 0 | 104 |
| C | C | 1 | 590 |
| | | | |

**C**

| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | B | 2 | 550 |
| B | B | 1 | 104 |
| C | C | 0 | 590 |
| D | D | 1 | 000 |

# DSDV – New Node

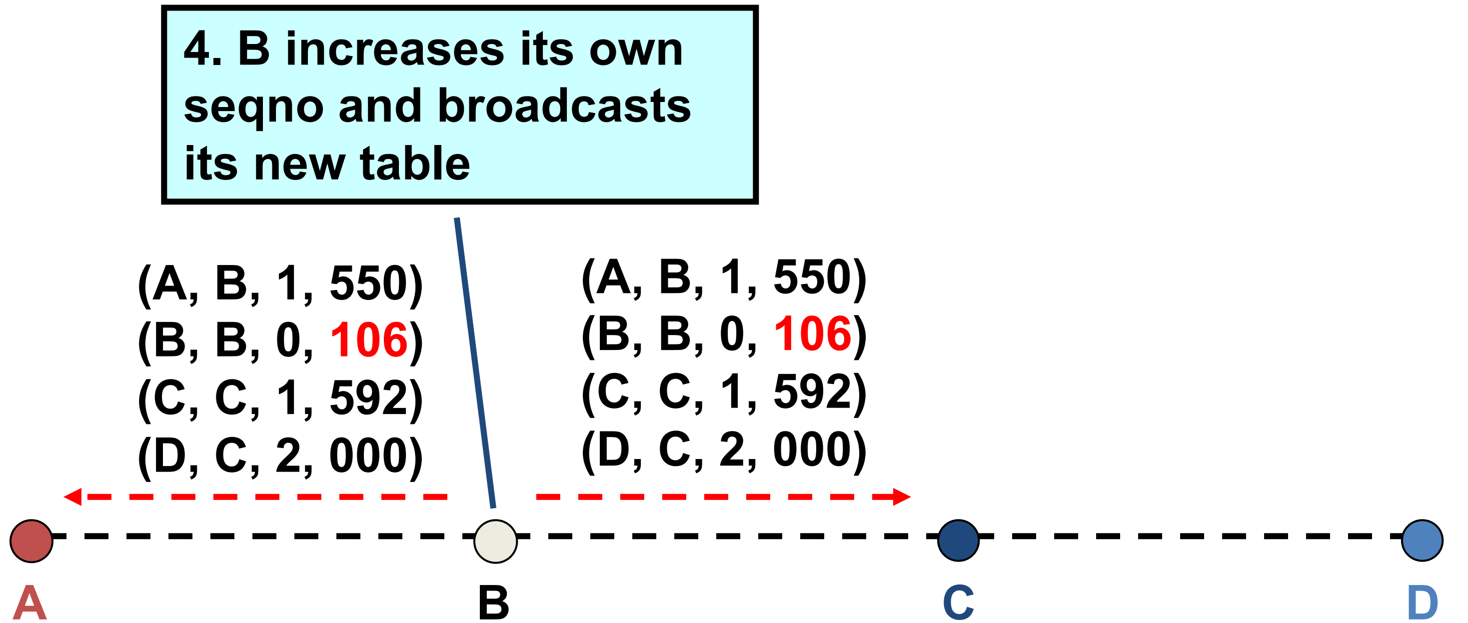



| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | A | 0 | 550 |
| B | B | 1 | 104 |
| C | B | 2 | 590 |
| | | | |

| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | A | 1 | 550 |
| B | B | 0 | 104 |
| C | C | 1 | 592 |
| D | C | 2 | 000 |

| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | B | 2 | 550 |
| B | B | 1 | 104 |
| C | C | 0 | 592 |
| D | D | 1 | 000 |

# DSDV – New Node




| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | A | 0 | 550 |
| B | B | 1 | 106 |
| C | B | 2 | 592 |
| D | B | 3 | 000 |

| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | A | 1 | 550 |
| B | B | 0 | 106 |
| C | C | 1 | 592 |
| D | C | 2 | 000 |

| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | B | 2 | 550 |
| B | B | 1 | 106 |
| C | C | 0 | 592 |
| D | D | 1 | 000 |

# Today

1. Distance Vector Routing

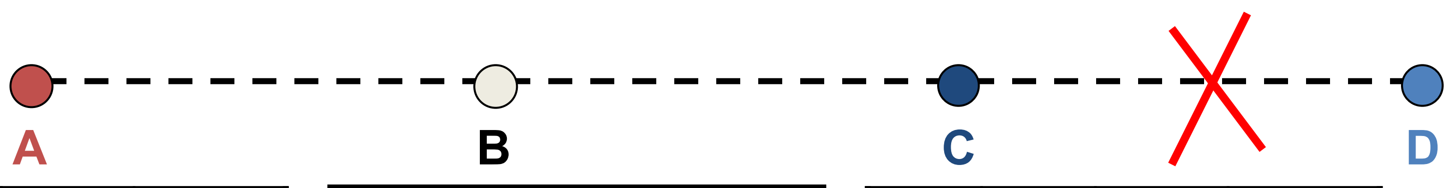
2. **Destination Sequenced Distance-Vector Routing (DSDV)**
   - New node join
   - **Broken link**
   - Route advertisement

3. Dynamic Source Routing (DSR)

4. Roofnet

# DSDV – Broken Link

- Suppose link **C ←→ D** **breaks**



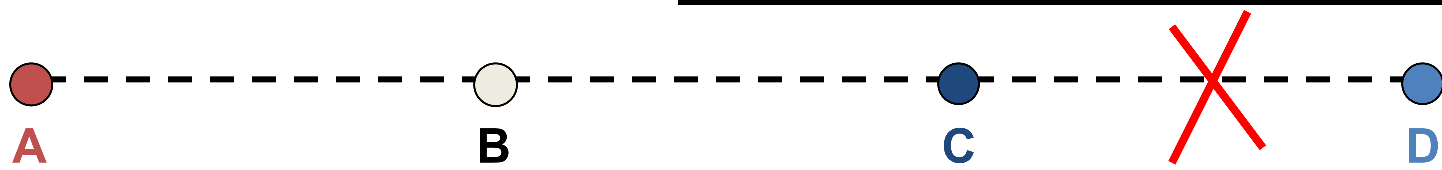

| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | A | 0 | 550 |
| B | B | 1 | 106 |
| C | B | 2 | 592 |
| D | B | 3 | 000 |

| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | A | 1 | 550 |
| B | B | 0 | 106 |
| C | C | 1 | 592 |
| D | C | 2 | 000 |

| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | B | 2 | 550 |
| B | B | 1 | 106 |
| C | C | 0 | 592 |
| D | D | 1 | 000 |

# DSDV – Broken Link

**1. Node C detects broken Link:**
**→ Increase Seq. No. by 1**
**(only case where not the destination sets the sequence number → odd number)**




| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | A | 0 | 550 |
| B | B | 1 | 106 |
| C | B | 2 | 592 |
| D | B | 3 | 000 |

| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | A | 1 | 550 |
| B | B | 0 | 106 |
| C | C | 1 | 592 |
| D | C | 2 | 000 |

| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | B | 2 | 550 |
| B | B | 1 | 106 |
| C | C | 0 | 592 |
| D | D | ∞ | 001 |

# DSDV: Routing Table Update Rule

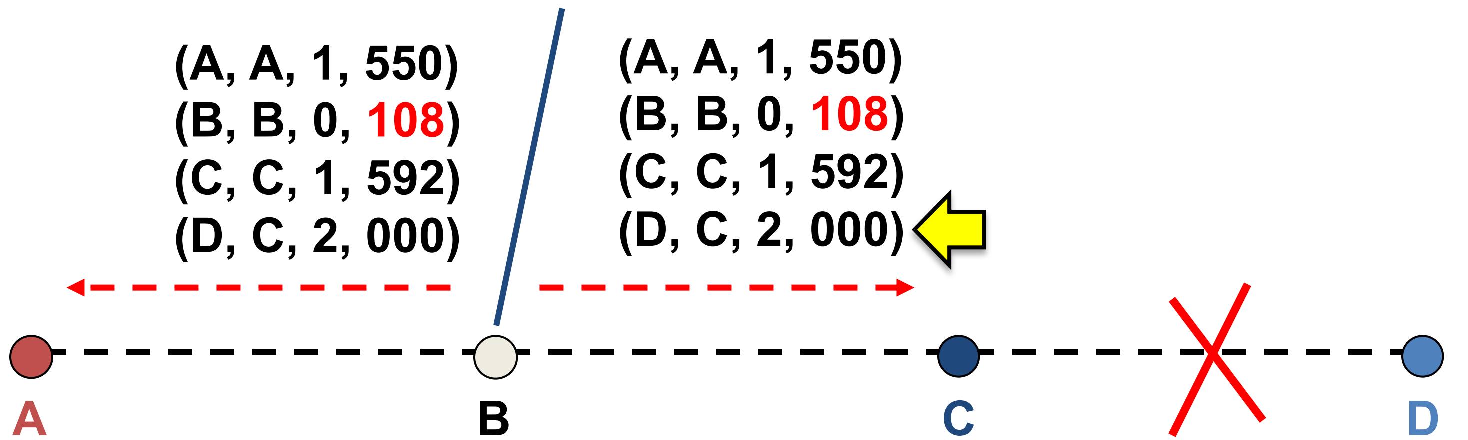
- **Rules to update routing table entry:**

- **Node N** gets routing advertisement from neighbor **Node P:**
  - Update routing table entry for **node E when:**
    - **Seq(E) in P's advertisement > Seq(E)** in **N's table**

# DSDV – Broken Link

- **B** next broadcasts its routing table

> - **No affect on C's entry for D (because 001 > 000)**
> - **No loop → no count to infinity**




| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | A | 0 | 550 |
| B | B | 1 | 108 |
| C | B | 2 | 592 |
| D | B | 3 | 000 |

| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | A | 1 | 550 |
| B | B | 0 | 108 |
| C | C | 1 | 592 |
| D | C | 2 | 000 |

| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | B | 2 | 550 |
| B | B | 1 | 108 |
| C | C | 0 | 592 |
| **D** | **D** | **∞** | **001** |

# Today

1. Distance Vector Routing

2. **Destination Sequenced Distance-Vector Routing (DSDV)**
   – New node join
   – Broken link
   – **Route advertisement**

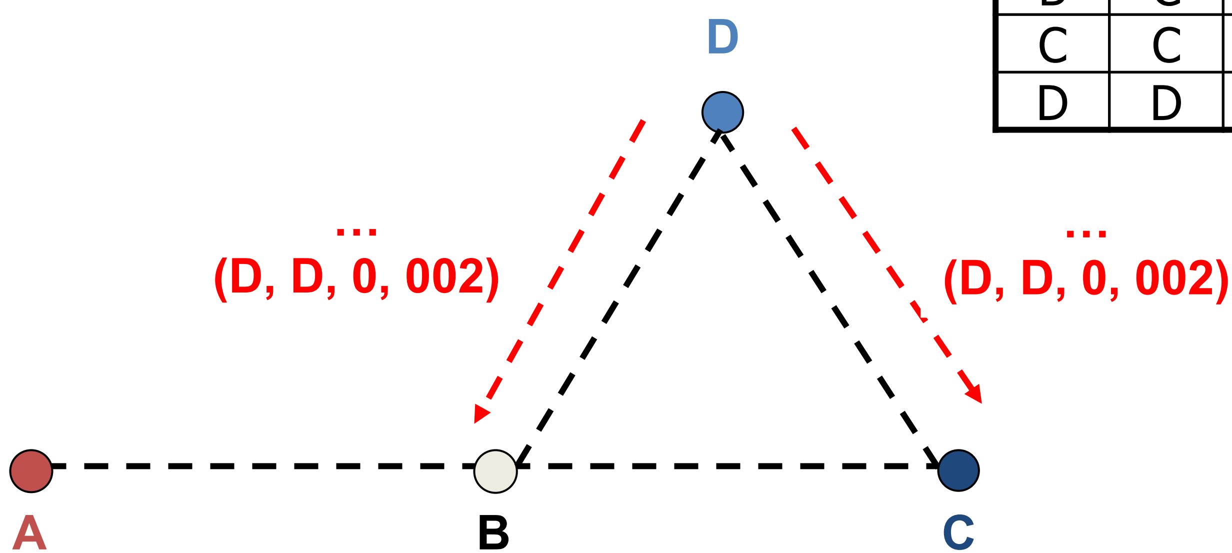
3. Dynamic Source Routing (DSR)

4. Roofnet

# Distance Vector – Route Advertisement

- **D** moves to another place and broadcasts its routing table

| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | C | 3 | 550 |
| B | C | 2 | 108 |
| C | C | 1 | 592 |
| D | D | 0 | 002 |




| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | A | 0 | 550 |
| B | B | 1 | 108 |
| C | B | 2 | 592 |
| D | B | 3 | 000 |

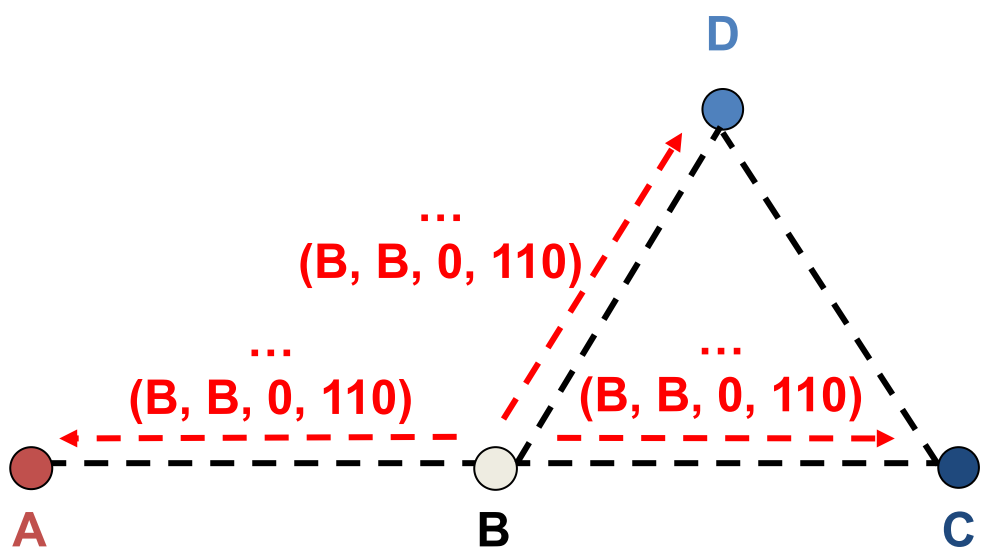
| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | A | 1 | 550 |
| B | B | 0 | 108 |
| C | C | 1 | 592 |
| D | D | 1 | 002 |

| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | B | 2 | 550 |
| B | B | 1 | 108 |
| C | C | 0 | 592 |
| D | D | 1 | 002 |

# Distance Vector – Route Advertisement

- **D** moves to another place and broadcasts its routing table
- **B** broadcasts its routing table

| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | B | 2 | 550 |
| B | B | 1 | 110 |
| C | C | 1 | 592 |
| D | D | 0 | 002 |




| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | A | 0 | 550 |
| B | B | 1 | 110 |
| C | B | 2 | 592 |
| D | B | 2 | 002 |

| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | A | 1 | 550 |
| B | B | 0 | 110 |
| C | C | 1 | 592 |
| D | D | 1 | 002 |

| Dest. | Next | Metric | Seq. |
|---|---|---|---|
| A | B | 2 | 550 |
| B | B | 1 | 110 |
| C | C | 0 | 592 |
| D | D | 1 | 002 |

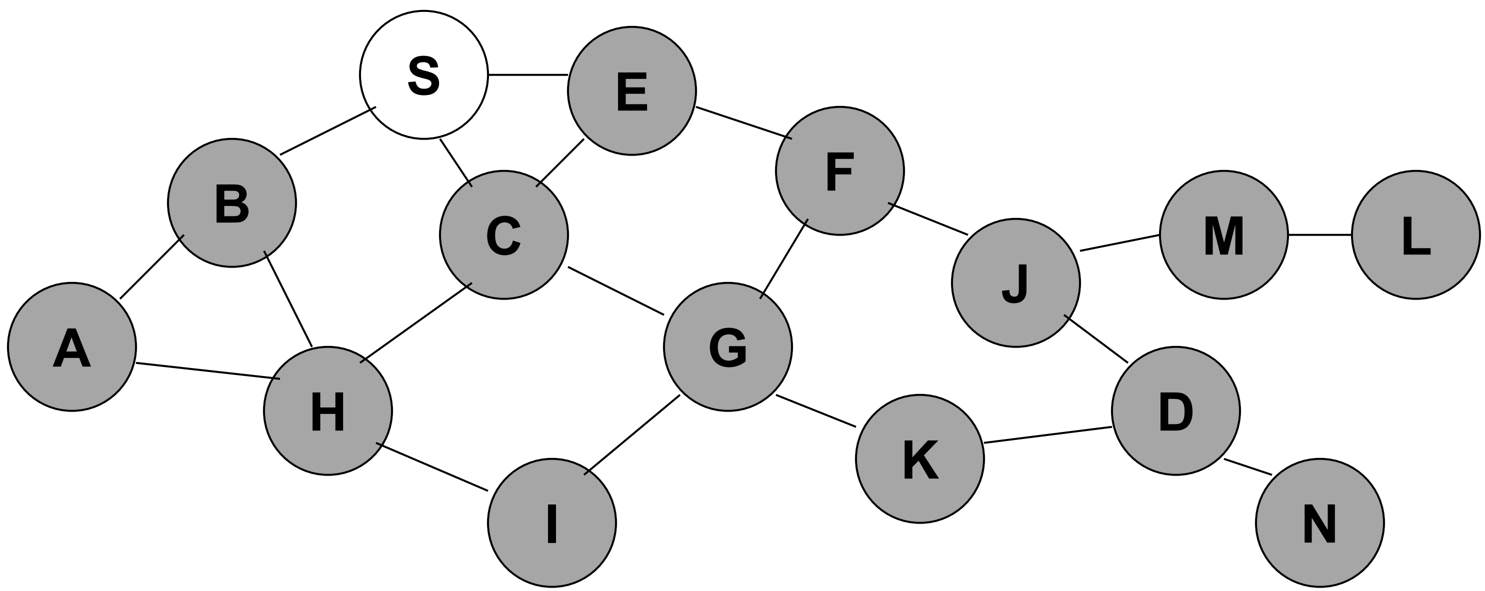
# Today

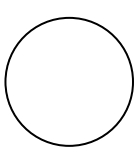
1. Distance Vector Routing
2. Destination Sequenced Distance-Vector Routing (DSDV)
3. **Dynamic Source Routing (DSR)**
4. Roofnet

# Dynamic Source Routing (DSR)

- **No periodic "beaconing"** from all nodes
- When node **S** wants to send a packet to node **D** (but doesn't know a route to D), **S** initiates a **route discovery**
- **S** **network-floods** a ***Route Request (RREQ)***
  - Each node **appends its own id when forwarding RREQ**

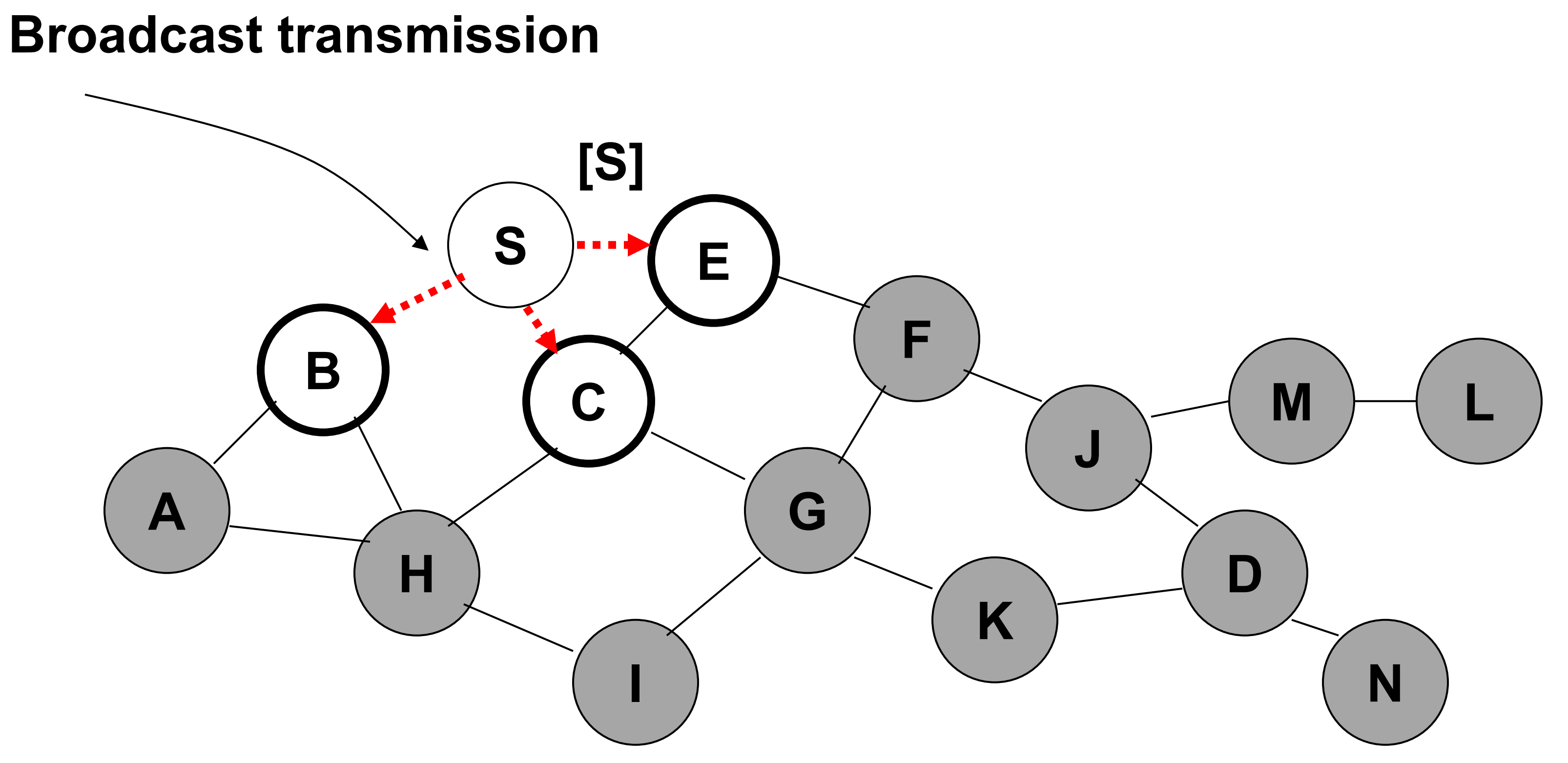
# Route Discovery in DSR



**Represents a node that has received RREQ for D from S**

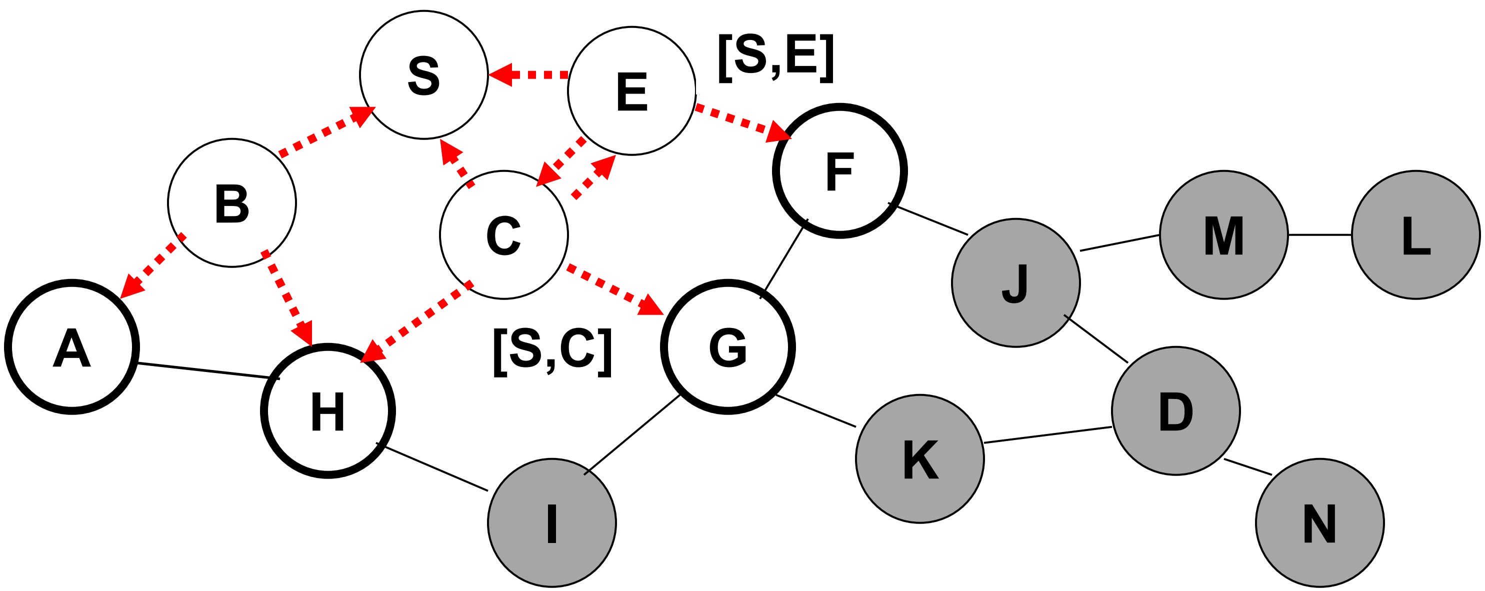
# Route Discovery in DSR




Represents transmission of RREQ

[X,Y] Represents list of identifiers appended to RREQ

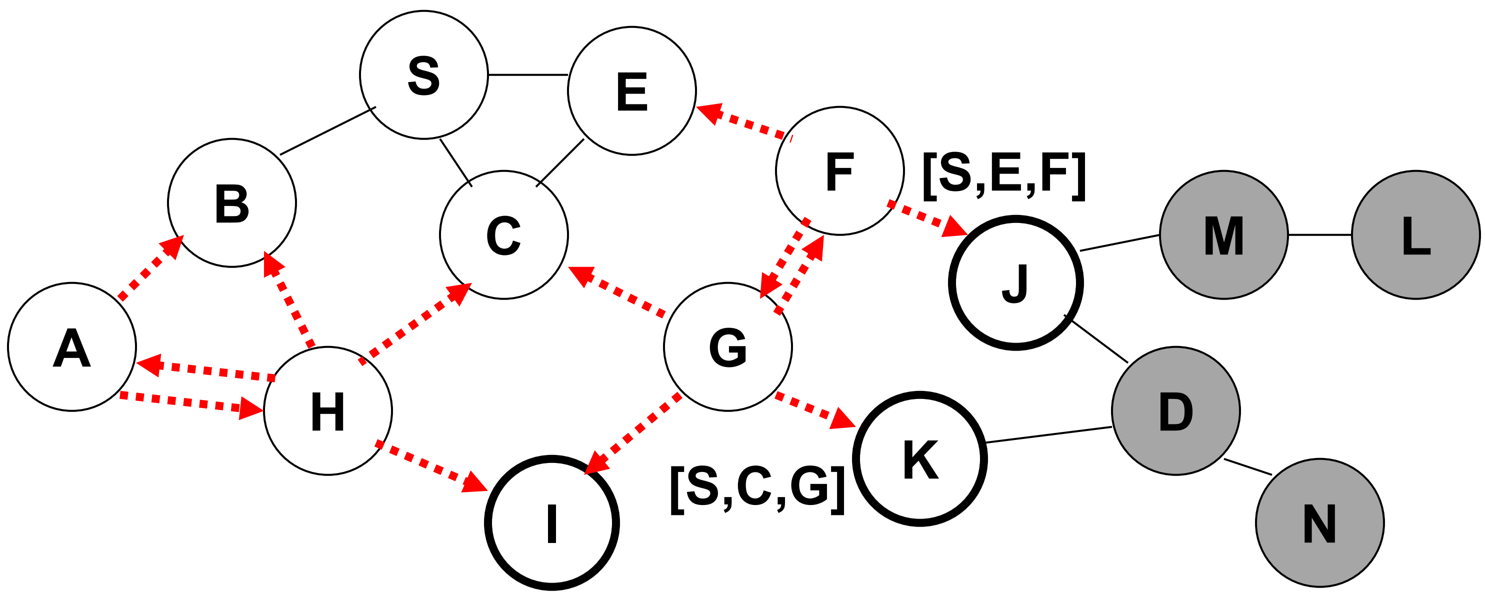
# Route Discovery in DSR




Represents transmission of RREQ

[X,Y] Represents list of identifiers appended to RREQ

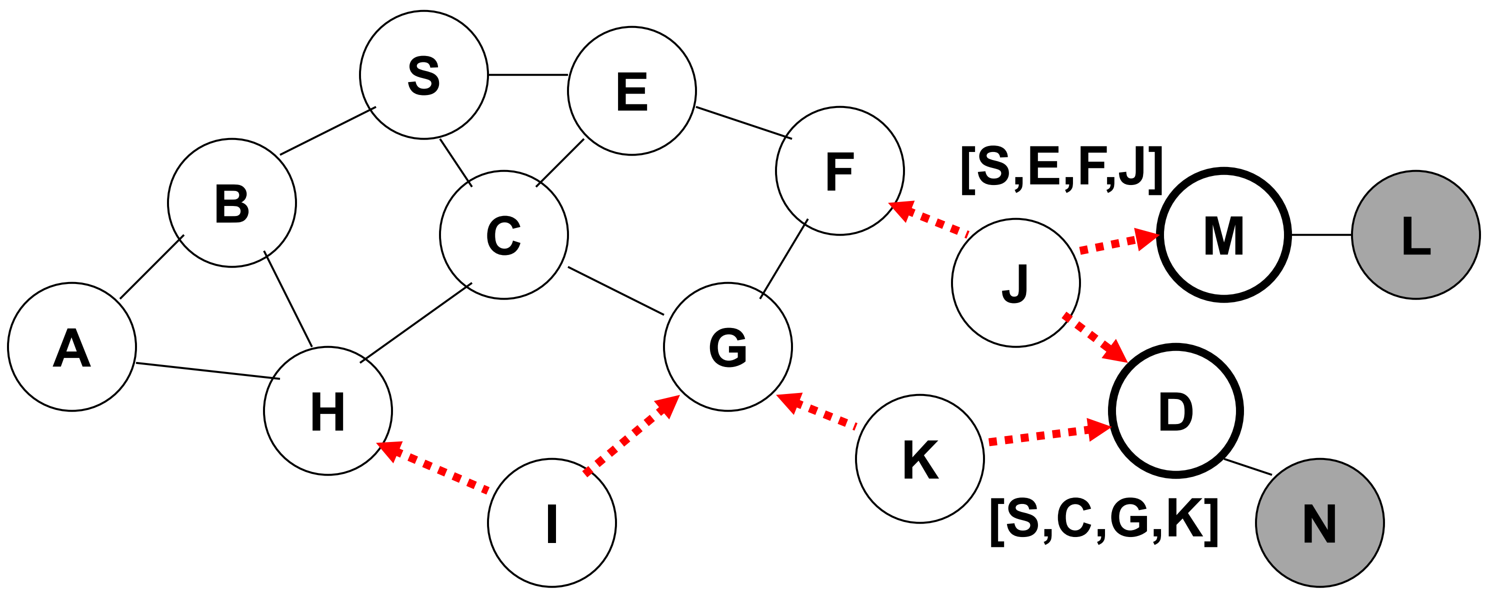
# Route Discovery in DSR




Represents transmission of RREQ

- Node C receives RREQ from G and H, but does not forward it again, because node C has already forwarded RREQ once

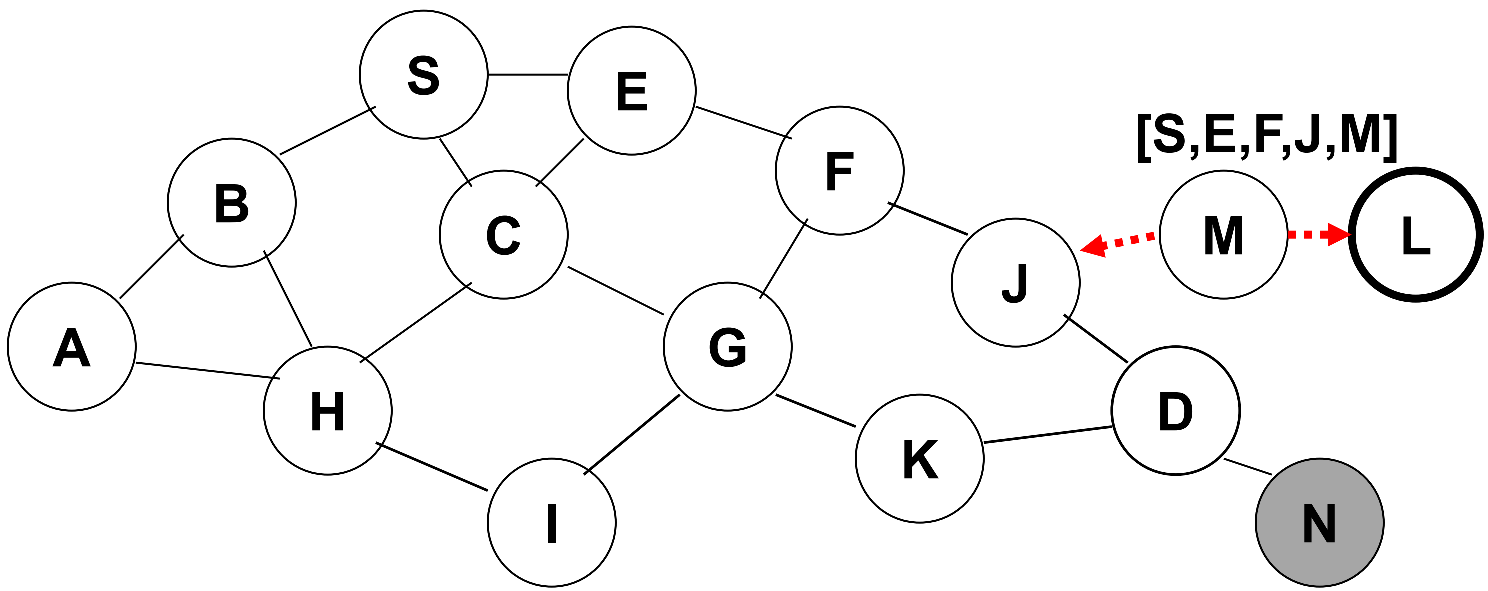
# Route Discovery in DSR




Represents transmission of RREQ

- Nodes J and K both broadcast RREQ to node D
- Since nodes J and K are hidden from each other, their transmissions may collide

# Route Discovery in DSR

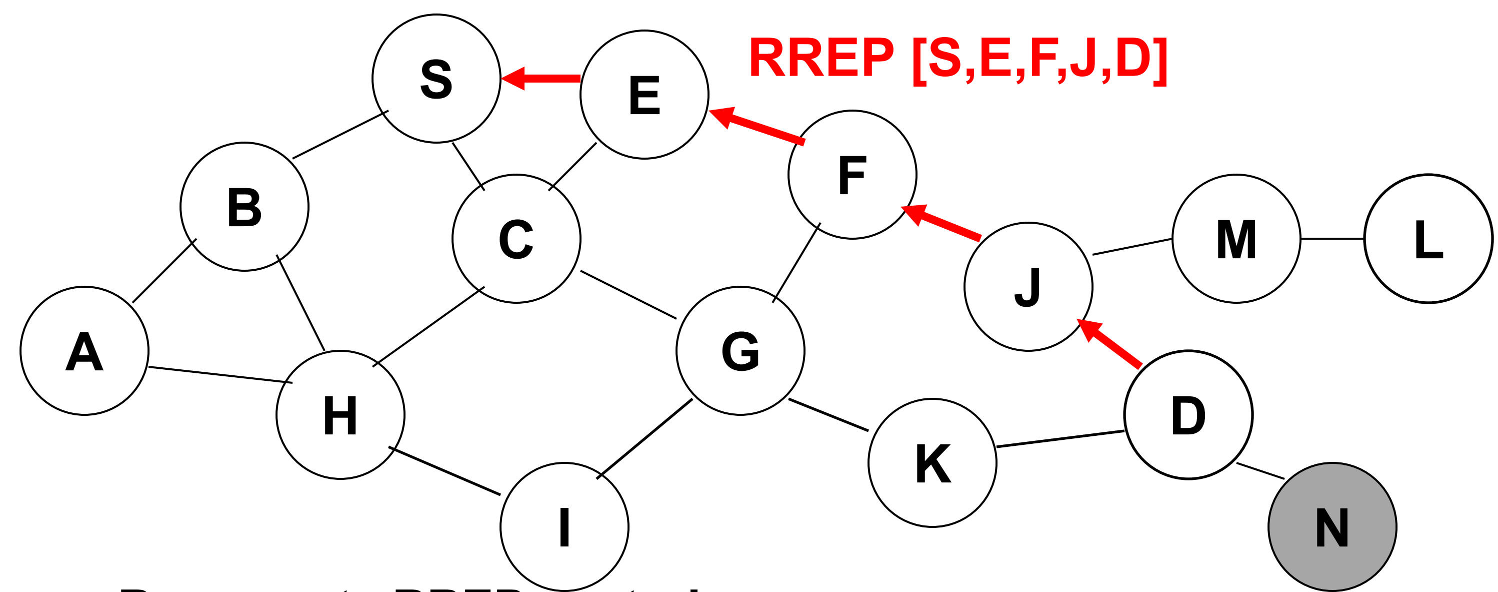



Represents transmission of RREQ

- Node D does not forward RREQ, because node D is the intended target of the route discovery

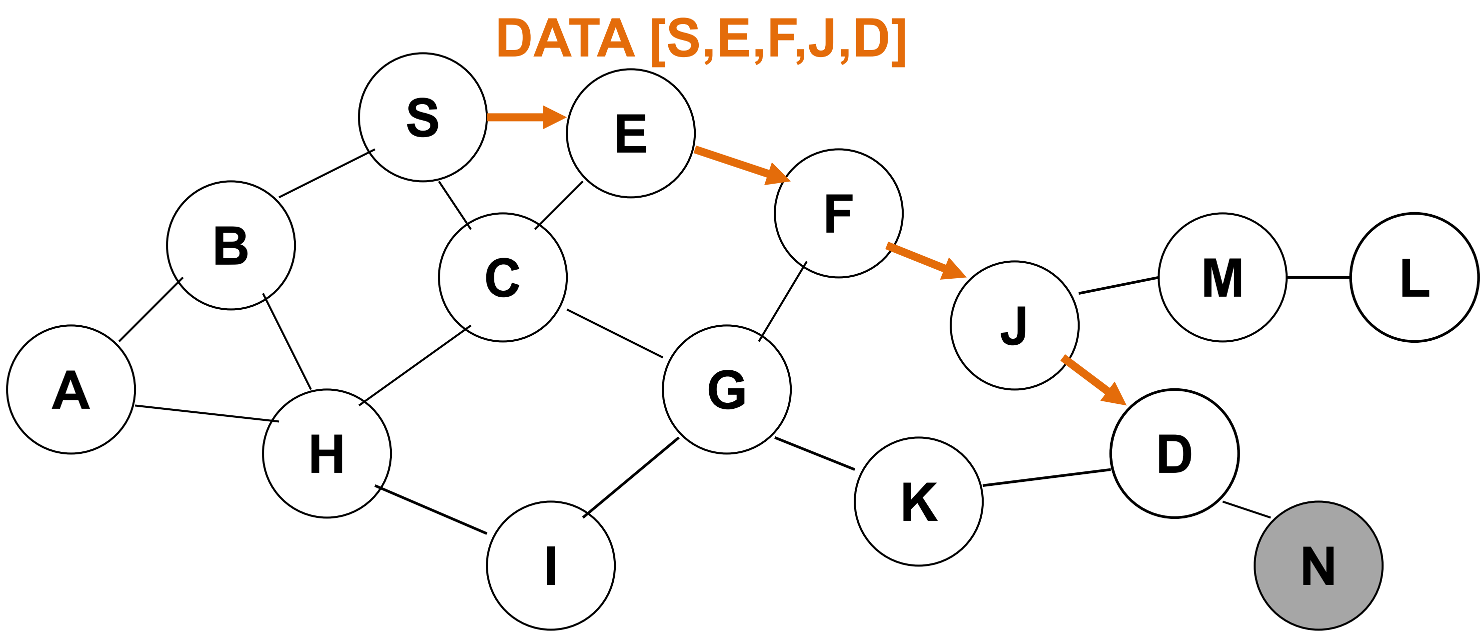
# Route Reply in DSR

- On receiving **first** RREQ, **D** sends a ***Route Reply*** **(RREP)**
  - RREP sent on route obtained by **reversing** the route in the received RREQ
  - RREP **includes the route** from **S** to **D** over which D received the RREQ



# Dynamic Source Routing (DSR)

- On receiving RREP, **S** caches route included therein
- When **S** sends a data packet to **D,** includes entire route in packet header
- Intermediate nodes use the **source route** included in packet to determine to whom packet should be forwarded



# Today

1. Distance Vector Routing
2. Destination Sequenced Distance-Vector Routing (DSDV)
3. Dynamic Source Routing (DSR)
4. **Roofnet**
   – Wireless mesh link measurements
   – Routing and bit rate selection
   – End-to-end performance evaluation

# Context, *ca.* 2000-2005

- **Mobile ad hoc networking** research
  - Mobile, hence highly dynamic topologies
  - Chief metrics: routing protocol overhead, packet delivery success rate, hop count
  - Largely evaluated in simulation

- **Roofnet,** a real mesh network **deployment**
  - Fixed, PC-class nodes
  - Motivation: shared Internet access in community
  - Chief metric: TCP throughput
  - "Test of time" system, led to **Cisco Meraki**

# Roofnet: Design Choices

1. Volunteer users host nodes at home
   – Open participation **without central planning**
   – No central **control** over topology

2. Omnidirectional rather than directional antennas
   – **Ease of installation**: no choice of neighbors/aiming
   – Links **interfere**, likely **low quality**

3. Multi-hop routing (not single-hop hot spots)
   – Improved **coverage** (path diversity)
   – Must build a routing protocol

4. Goal: high TCP throughput

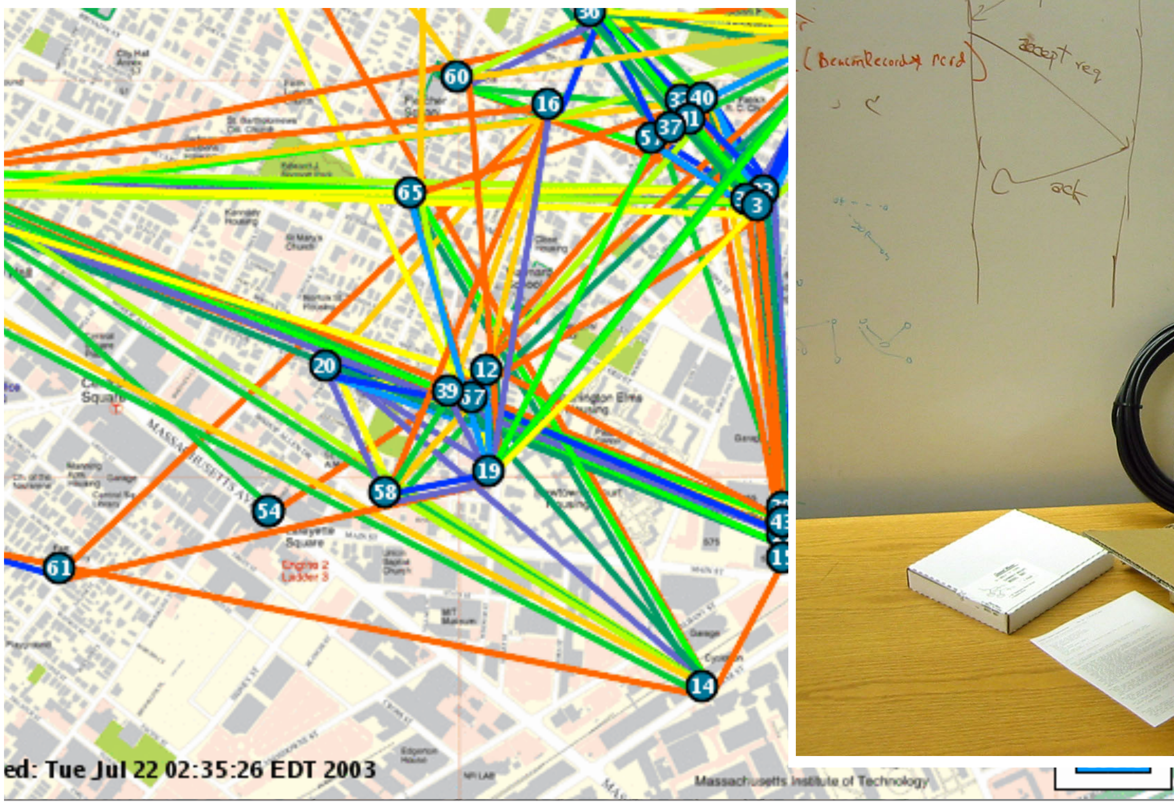
# Roofnet: Goals and non-goals

- Each part of the mesh architecture had been **previously examined** in isolation

- **Paper contribution:** A systematic evaluation of whether architecture can achieve goal of providing Internet access

- **Stated non-goals for paper:**
  - Throughput of multiple concurrent flows
  - Scalability in number of nodes
  - Design of routing protocols

# Roofnet deployment





- Each node: PC, 802.11b card, roof-mounted omni antenna

# Hardware design

- PC Ethernet interface provides wired Internet for user

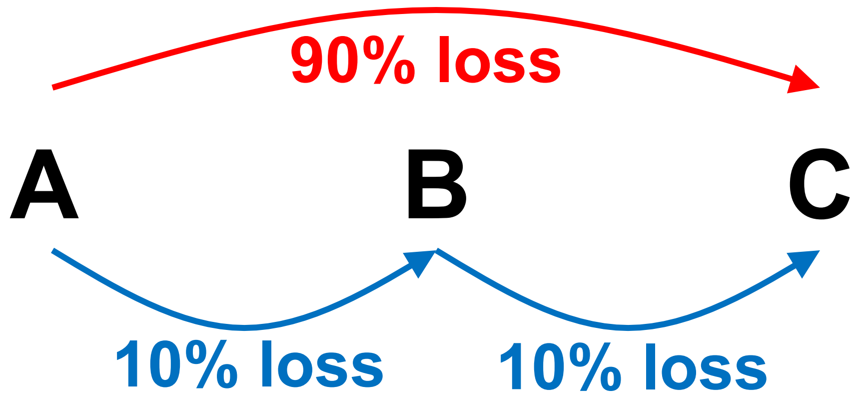
- Omnidirectional antenna in **azimuthal** direction
  - 3 dB **vertical** beam width of 20 degrees
    - Wide beam sacrifices gain but **removes the need** for perfect vertical **antenna orientation**

- **802.11b** radios (*Intersil Prism 2.5* chipset)
  - 200 mW transmit power
  - All share same 802.11 channel (frequency)

# Internet gateways

- Node sends DHCP request on Ethernet then tests reachability to Internet hosts
  - Success indicates node is an **Internet gateway**
    - Gateways **translate** between Roofnet and Internet IP address spaces
- Roofnet nodes track gateway used for each open TCP connection they originate
  - If best gateway changes, open connections **continue to use gateway** they already do
- If a Roofnet gateway fails, **existing** TCP connections through that gateway **will fail**

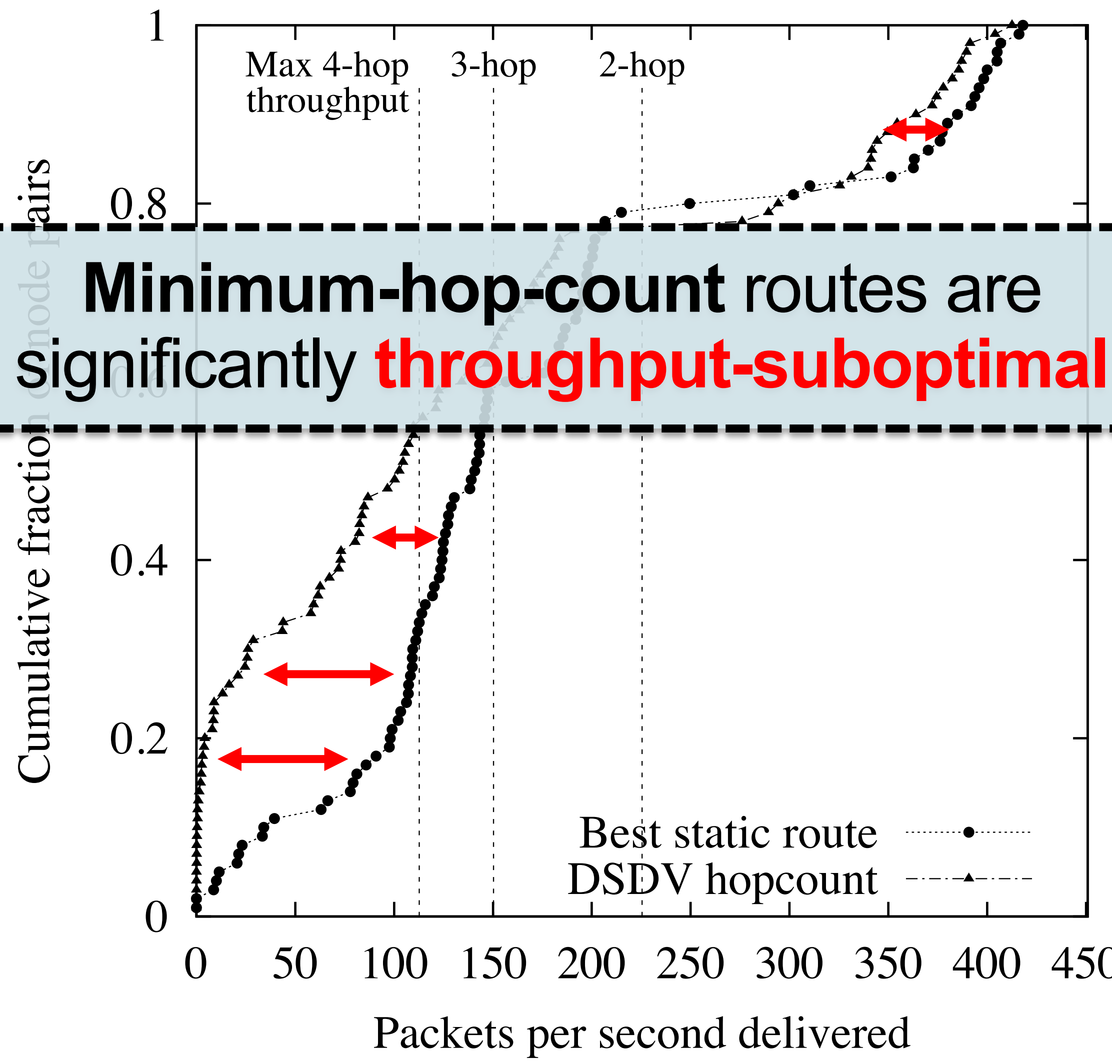
# Example: Varying link loss rates




- A → C: 1 hop; **high loss**
- A → B → C: 2 hops; **lower loss**

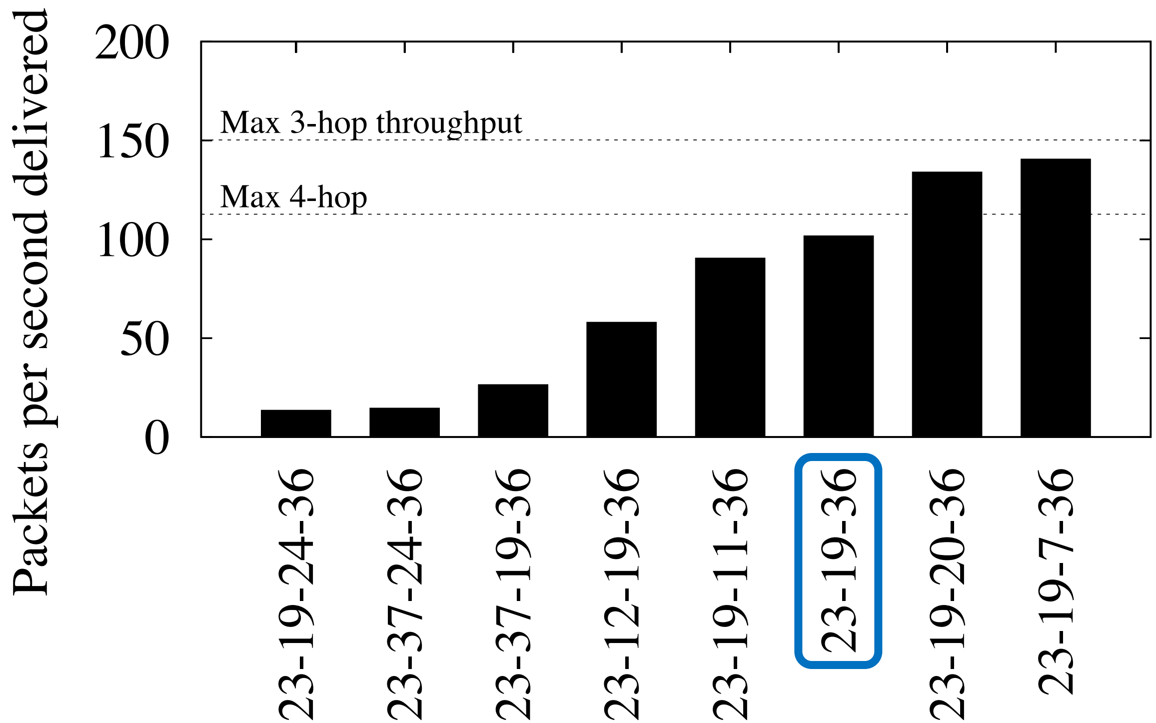
- But **does this happen** in practice?

# Hop count and throughput (1)



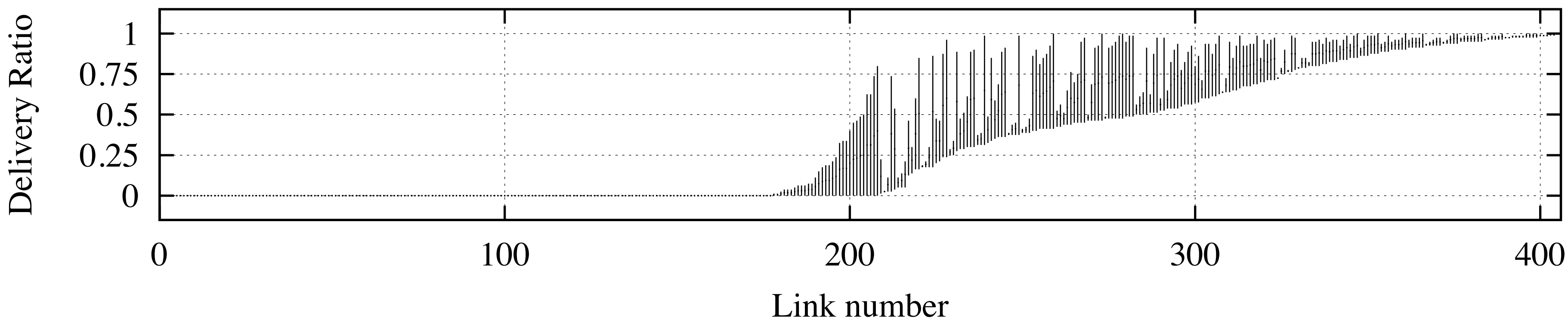

**Minimum-hop-count** routes are significantly **throughput-suboptimal**

# Hop count and throughput




- Two-hop path is **suboptimal**
- Some **3-hop paths better, some worse** than 2-hop

# Link loss is high and asymmetric




- Vertical bar ends = loss rate on 1 link in each direction
- Many links **asymmetric** and **very lossy in ≥ 1 way**
- **Wide range** of loss rates

# Routing protocol: Srcr

- Each link has an associated ***metric*** (not necessarily 1!)
- Data packets contain **source routes**

- Nodes keep **database of link metrics**
  – Nodes write current metric into source route of all forwarded packets
  – **DSR-like:** Nodes flood ***route queries*** when they can't find a route; queries accumulate link metrics
    - Route queries contain route from requesting node
  – Nodes cache overheard link metrics

- **Dijkstra's algorithm** computes source routes

# Link metric: Strawmen

- *Discard links with loss rate above a threshold?*
  - Risks **unnecessarily disconnecting** nodes

- *Product of link delivery rates → prob. of e2e delivery?*
  - **Ignores inter-hop interference**
    - Prefers 2-hop, 0% loss route over 1-hop, 10% loss route (but latter is **double throughput**)

- *Throughput of highest-loss link on path?*
  - Also **ignores inter-hop interference**

# ETX: Expected Transmission Count

- ***Link ETX:*** predicted number of transmissions
  - Calculate link ETX using forward, reverse delivery rates
  - To avoid retry, data packet **and** ACK must succeed
  - **Link ETX = 1 / ($d_f \times d_r$)**
    - $d_f$ = forward link delivery ratio (data packet)
    - $d_r$ = reverse link delivery ratio (ack packet)
- ***Path ETX:*** sum of the link ETX values on a path

# Measuring link delivery ratios

- Nodes periodically send broadcast ***probe*** packets
  - All nodes know the **sending period** of probes
  - All nodes **compute loss rate** based on how many probes arrive, per measurement interval
- Nodes **enclose these loss measurements** in their transmitted probes
  - *e.g.* **B** tells node **A** the link delivery rate from **A** to **B**

# Multi-bitrate radios

- ETX assumes all radios run at same bit-rate
  - But 802.11b rates: {1, 2, 5.5, 11} Mbit/s
- **Can't compare** two transmissions at 1 Mbit/s with two at 2 Mbit/s
- **Solution:** Use expected **time** spent on a packet, rather than transmission count

# ETT: Expected Transmission Time

- ACKs always sent at 1 Mbps, data packets 1500 bytes

- Nodes send 1500-byte broadcast probes at every bit rate *b* to compute ***forward link delivery rates*** $\mathbf{d_f(b)}$
  - Send 60-byte (min size) probes at 1 Mbps → $\mathbf{d_r}$

- At each bit-rate *b*, $ETX_b = 1 / (d_f(b) \times d_r)$
- For packet of length *S*, $ETT_b = (S / b) \times ETX_b$
- **Link ETT** = $\min_b (ETT_b)$

# ETT: Assumptions

- Path throughput estimate *t* is given by

$$t = \frac{1}{\sum_{\text{hop } i \in \text{path}} \frac{1}{t_i}}$$

  - $t_i$ = throughput of hop *i*

- *Does ETT maximize throughput?* No!

1. Underestimates throughput for long (≥ 4-hop) paths
   - Distant nodes can send simultaneously

2. Overestimates throughput when transmissions on different hops collide and are lost

# Roofnet evaluation

- TCP bulk transfers between **all node pairs** but always a **single flow at a time**
  - But background traffic present: **users always active**
- **Results:**
  1. **Wide spread** of end-to-end throughput across pairs
  2. **“Chain forwarding”** indeed creates **interference**
  3. **Lossy links** indeed **useful** in practice

# Wireless Mesh Networks: Evolving Routing

- **DSDV** took DV out of wired (more static) networks
  - Better **coped with dynamism**
- **DSR** **addressed protocol overheads** of routing
- **ETX and ETT abolished hop-count** as a viable metric
  - Replaced it with **throughput as the metric**