Midterm Review

DSR, AODV, DSDV, Sequence Numbers, Link Metrics

Outline

- 802.11 transmission channels
- DSR, AODV, DSDV
- Multiple transmission channels
- Sequence numbers to prevent loops for distance vector algorithms
- How to compute ETX and ETT in practice
802.11 Transmission Channels

- 802.11 = 802.11b, 802.11g, 802.11a, 802.11n
- 802.11b/g: ISM band at 2.5 GHz
  - 2.400-2.500 GHz
- 802.11a: 5 GHz U-NII band
  - From 5.15 to 5.825 GHz

DSDV

- DSDV: Destination Sequence Distance Vector
- Distance vector adapted to wireless
- Sequence number against loops
- Full dump infrequently, incremental updates more frequently
**DSR**
- On-demand algorithm
- Source routing
- RREQ, RREP, RERR
- Caching
- Many optimizations

**AODV**
- On-demand algorithm
- Distance vector: routing table at nodes
- RREQ, RREP
  - Path discovery, reverse path setup, forward path setup
- Sequence number
**Distance Vector Example**

- Symmetric links, link cost = 1
- A, B... E are addresses
- Local knowledge

Example borrowed from "Routing in the Internet", Huitema, 1995

**Cold Start**

<table>
<thead>
<tr>
<th>From A to</th>
<th>Link</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Local</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>From B to</th>
<th>Link</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Local</td>
<td>0</td>
</tr>
</tbody>
</table>

Tx: DV(A): A=0 [1,3]
**Update at B and D**

- **Tx**: DV(B): B=0, A=1 [1,2,4]
- **Tx**: DV(D): D=0, A=1 [3,6]

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**Message from B Received First**

- **Rx**: DV(B): B=0, A=1
- **Rx**: DV(D): D=0, A=1

---

**From A to** | **Link** | **Cost**  
---|---|---  
A | Local | 0  
B | 1 | 1  
D | 3 | 1

**From B to** | **Link** | **Cost**  
---|---|---  
B | Local | 0  
A | 1 | 1

**From D to** | **Link** | **Cost**  
---|---|---  
D | Local | 0  
A | 3 | 1

**From C to** | **Link** | **Cost**  
---|---|---  
C | Local | 0  
B | 2 | 1  
A | 2 | 1

**From E to** | **Link** | **Cost**  
---|---|---  
E | Local | 0  
B | 4 | 1  
A | 4 | 2
**E Receives Message From D**

- **Rx**: DV(D): D=0, A=1
- **Tx**: DV(A): A=0, B=1, D=1 [1,3]
- **Tx**: DV(C): C=0, B=1, A=2 [2,5]
- **Tx**: DV(E): E=0, B=1, A=2, D=1 [4,5,6]

No update of the entry for A

Routing Tables at B, D and E are Updated

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**From B to**

<table>
<thead>
<tr>
<th>From B to</th>
<th>Link</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Local</td>
<td>0</td>
</tr>
<tr>
<td>A</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>C</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>E</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

**From D to**

<table>
<thead>
<tr>
<th>From D to</th>
<th>Link</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Local</td>
<td>0</td>
</tr>
<tr>
<td>A</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>E</td>
<td>6</td>
<td>1</td>
</tr>
</tbody>
</table>

**From E to**

<table>
<thead>
<tr>
<th>From E to</th>
<th>Link</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>Local</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>A</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>D</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>
And New DVs are Sent

- DV(B): B=0, A=1, D=2, C=2, E=1 [1,3,4]
- DV(D): D=0, A=1, B=2, E=1 [3,6]
- DV(E): E=0, B=1, A=2, D=1, C=1 [4,5,6]

Routing Tables at A, C and D are Updated

<table>
<thead>
<tr>
<th>From C to</th>
<th>Link</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Local</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>A</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>E</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>D</td>
<td>5</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>From A to</th>
<th>Link</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Local</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>D</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>E</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>From D to</th>
<th>Link</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>Local</td>
<td>0</td>
</tr>
<tr>
<td>A</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>E</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>6</td>
<td>2</td>
</tr>
</tbody>
</table>

- No more update necessary
If Link 1 Breaks?

- Update at A and B: inf for all routes through link 1

<table>
<thead>
<tr>
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<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Local</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>Inf</td>
</tr>
<tr>
<td>D</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>Inf</td>
</tr>
<tr>
<td>E</td>
<td>1</td>
<td>Inf</td>
</tr>
</tbody>
</table>

Distance Vector Issues: Temporary Loop

- Cost(5)=10
- Link 2 breaks

<table>
<thead>
<tr>
<th>From X to C</th>
<th>Link</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>B</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>Local</td>
<td>0</td>
</tr>
<tr>
<td>D</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>E</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>
**Distance Vector Issues: Temporary Loop**

- **Diagram:**
  - Nodes: A, B, C, D, E
  - Links: A-B, B-C, C-D, D-E, E-A
  - Costs: A-B=2, B-C=∞, C-D=3, D-E=3, E-A=2

- **Table:**

<table>
<thead>
<tr>
<th>From X to C</th>
<th>Link</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>B</td>
<td>2</td>
<td>Inf</td>
</tr>
<tr>
<td>C</td>
<td>Local</td>
<td>0</td>
</tr>
<tr>
<td>D</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>E</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

- **Process:**
  - B notice failure
  - A send DV refresh before B:
    - DV(A) A=0, B=1, C=2, D=1, E=2
  - B send DV update
    - DV(B) A=1, B=0, C=3, D=2, E=1
  - Temp. loop A-B to C

**Distance Vector Issue: Count to Infinity**

- **Diagram:**
  - Nodes: A, B, C, D, E
  - Links: A-B, B-C, C-D, D-E, E-A
  - Costs: A-B=1, B-C=Inf, C-D=Inf, D-E=Inf, E-A=4

- **Table:**

<table>
<thead>
<tr>
<th>From D to</th>
<th>Link</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>Local</td>
<td>0</td>
</tr>
<tr>
<td>A</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>3</td>
<td>Inf</td>
</tr>
<tr>
<td>E</td>
<td>6</td>
<td>Inf</td>
</tr>
<tr>
<td>C</td>
<td>6</td>
<td>Inf</td>
</tr>
</tbody>
</table>

- **Process:**
  - Link 6 breaks after link 2
  - D notice failure
  - A send DV refresh before D:
    - DV(A) A=0, B=3, C=3, D=1, E=3
  - Temp. loop A-B
Split Horizon and Co.

- Split horizon: if A to X through B, then B should not try to reach X through A
  - A does not announce route to X to B
- With poisonous reverse: announce route but set cost to Inf

Split Horizon is not Enough

- Split Horizon: DV(A) empty
- With poisonous reverse:
  - DV(A)B=Inf, D=Inf, C=Inf, E=Inf
Split Horizon Does Not Prevent all Loops

- E-D failure

```
E
B
C

1
2
4
5
6
```

- $DV(E) \rightarrow D=\text{Inf} [4,5]$, tx error on 5
- $DV(C) \rightarrow E=\text{Inf} \rightarrow [5]$, $DV(C) \rightarrow E=1, D=2 \rightarrow [2]$
- $DV(B) \rightarrow D=3 \rightarrow [4]$

<table>
<thead>
<tr>
<th>From X to D</th>
<th>Link</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>C</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>E</td>
<td>6</td>
<td>Inf</td>
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</table>

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<tbody>
<tr>
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<td>Inf</td>
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<tr>
<td>C</td>
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<td>2</td>
</tr>
<tr>
<td>E</td>
<td>6</td>
<td>Inf</td>
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<tbody>
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<tr>
<td>C</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>E</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

DSDV Use Destination Sequence Numbers to Avoid Loops

- (destination) sequence number for each node
  - Each node increments and appends its sequence number when sending its local routing table
  - This sequence number attached to route entries created for this node
DSDV Use Destination Sequence Numbers to Avoid Loops

<table>
<thead>
<tr>
<th>From B to</th>
<th>Link</th>
<th>Cost</th>
<th>Seq</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
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<td>3</td>
<td>50</td>
</tr>
<tr>
<td>B</td>
<td>Local</td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td>C</td>
<td>2</td>
<td>1</td>
<td>70</td>
</tr>
<tr>
<td>D</td>
<td>4</td>
<td>2</td>
<td>80</td>
</tr>
<tr>
<td>E</td>
<td>4</td>
<td>1</td>
<td>90</td>
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</table>

From C to

<table>
<thead>
<tr>
<th>Link</th>
<th>Cost</th>
<th>Seq</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>B</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>Local</td>
<td>0</td>
</tr>
<tr>
<td>D</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>E</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>

From E to

<table>
<thead>
<tr>
<th>Link</th>
<th>Cost</th>
<th>Seq</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>B</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>D</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>E</td>
<td>Local</td>
<td>0</td>
</tr>
</tbody>
</table>

Destination Sequence Number and Routing Update

1. If $S(X) > S(Y)$, then $X$ ignores the routing information received from $Y$
2. If $S(X) = S(Y)$, and cost of going through $Y$ is smaller than the route known to $X$, then $X$ sets $Y$ as the next hop to $Z$
3. If $S(X) < S(Y)$, then $X$ sets $Y$ as the next hop to $Z$, and $S(X)$ is updated to equal $S(Y)$
With Previous Example

- $DV(E) \ldots D=\text{Inf}(80) [4,5]$, tx error on 5
- $DV(C) E=\text{Inf}(90), \ldots [5]$, $DV(C) E=1(90), D=2(80) [2]$
  - Identical sequence number, but longer route: rule 2, update rejected

AODV Uses “Route Request” Sequence Number

- E unable to forward packet P (from E to D) on link 6, generates a RERR message
- E increments the destination sequence number for D cached at E
- Incremented sequence number $N$ included in RERR
- E initiates RREQ for D, use destination sequence number $> N$

- D receives RREQ with destination sequence number $N$, D set its sequence number to $N$, unless it is already larger than $N
AODV Sequence Number Rule

- If RREQ sequence number > sequence number in table, intermediate node does not answer RREQ

With Previous Example

- E sends to D, link 6 breaks
- E sends RREP(D,Inf), lost on link 4
- E sends RREQ(D,N+2)
- B does not send RREP since N+2 > N
Non-Uniform Packet Reception Probability

- Contour prob. of packet reception around a single node
- Setup: around 160 nodes in a grid with 60 cm spacing
- Heavy-tail behavior

Performance of Hop Count

- Setup: 100 random node pairs, throughput CDF, DSDV with min. hop-count vs “best” route
Motivation for a Better Metric

- Distribution of link loss ratio
  - Many links are asymmetric, wide range of loss ratios

Same Hop Count, Different Throughput

Run R1: 1 mW, 134-byte packets
**Expected Transmission Count (ETX)**

- In theory:
  \[ ETX = \frac{1}{d_f \times d_r} \]
  - \(d_f\): forward delivery ratio
  - \(d_r\): reverse delivery ratio
  - Assumptions: fixed rate, fixed power, ignore packet size

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**ETX Original Implementation**

- Each node broadcast probe of fixed size at *average* period \(\tau\)
  \[ r(t) = \frac{\text{count}(t - v, t)}{w / \tau} \]
  - Typical: size 134 bytes, \(w = 0, \tau = 1\)
  - Each probe contains \# probes received from each neighbor

- Use 802.11 broadcast frames, 1 Mbps, 1 mW
  - No ack, no retransmission
Packet Loss Varies with Packet Size

- Packet size typically larger than probe size (193 bytes with overhead)

A High-Throughput Path Metric for Multi-Hop Wireless Routing, De Couto et al., 2003

Accuracy of ETX

- ETX overestimates packet delivery (why? Probably underestimate ACK delivery ratio)
ETX in OLSR: olsr.org implementation

- Link quality computed from HELLO packets reception
  - Sent every two seconds

- New LQ Hello messages (broadcast link quality computed for each neighbor)
  - Non RFC 3626 compliant

- Extend TC messages (how good links are)
  - Non RFC 3626 compliant

http://www.olsr.org/docs/README-Link-Quality.html

Expected Transmission Time (ETT)

- Start with ETX, multiply with link bandwidth
  \[ ETT = \frac{c}{B} \times ETX \]
  - S: packet size, B: link bandwidth (raw data rate)

- How to find B?
  - Fix rate / autorate / ...
  - Use measurement: packet pairs

Routing in Multi-Radio, Multi-Hop Wireless Mesh Networks, Draves et al., 2004
How to Compute the ETT = Compute B

- Packet pairs:
  - Send two packets back-to-back: a short (137) followed by a long (1137)
  - Measure time difference of reception
  - Send back to transmitter
  - Min of 10 consecutive samples, divide size of long packet by min value

- Implementation
  - 802.11 broadcast frame for loss rate
  - Unicast packet for bandwidth (because use of autorate)

- Why not RTT: $O(n^2)$

Accuracy of Packet Pairs Measurements
Another ETT Implementation

- Measure delivery probability and compute ETT
  - Delivery prob. measurement
    - For each 802.11b rate: send periodic 1500-byte broadcasts
    - Periodic minimum size 60-byte broadcast at 1 Mbps
    - Nodes keep track of received broadcasts and report back to neighbors
      - Delivery prob. = fraction $rx@1500 \times fraction \, rx@60$
      - Accounts for ACK, for each rate
  - ETT computation (for best delivery prob.)
    - Delivery prob. * Transmission time of 1500-byte frame

Architecture and Evaluation of an Unplanned 802.11b Mesh Network, Bicket et al., 2005

ETX vs Hop Count with Mobility

- Scenario: 45 1-min. TCP transmissions with a mobile sender in a static mesh network

Comparison of Routing Metrics for Static Multi-Hop Wireless Networks, Draves et al., 2004
**DSR with ETX**

- **DSR Modifications**
  - Link cache, run Dijkstra to find best route (at source)
  - ETX measurement using periodic broadcast link probes
  - RREQ forwarding: forwarder address + ETX of incoming link
  - IF RREQ with better accumulated metric for given ID: forward again
  - Metrics included in RREP
  - No overhearing, no salvaging, no reply from cache

---

**DSDV with ETX**

- Use short (134 bytes payload) probe every second
- Remember probes over last 10 seconds
Do We Gain Anything?

- Setup: 100 random node pairs, throughput CDF

A High-Throughput Path Metric for Multi-Hop Wireless Routing, De Couto et al., 2003

DSDV: Hop Count vs ETX

- Setup: 40 pairs from the 100 random node pairs
- Higher tx power increases connectivity
**DSR: Hop Count vs ETX**

- ETX helps for initial route choice

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**DSR with feedback: Hop Count vs ETX**

- Failure feedback removes low throughput routes
Summary

- Link metrics play a crucial role in the performance of a routing algorithm for wireless networks
- They are still an active area of research
- In practice (today), ETX appears to be the most and widely used metric
- Look at the system overall result