6.808 Mobile and Sensor Computing

aka IoT Systems

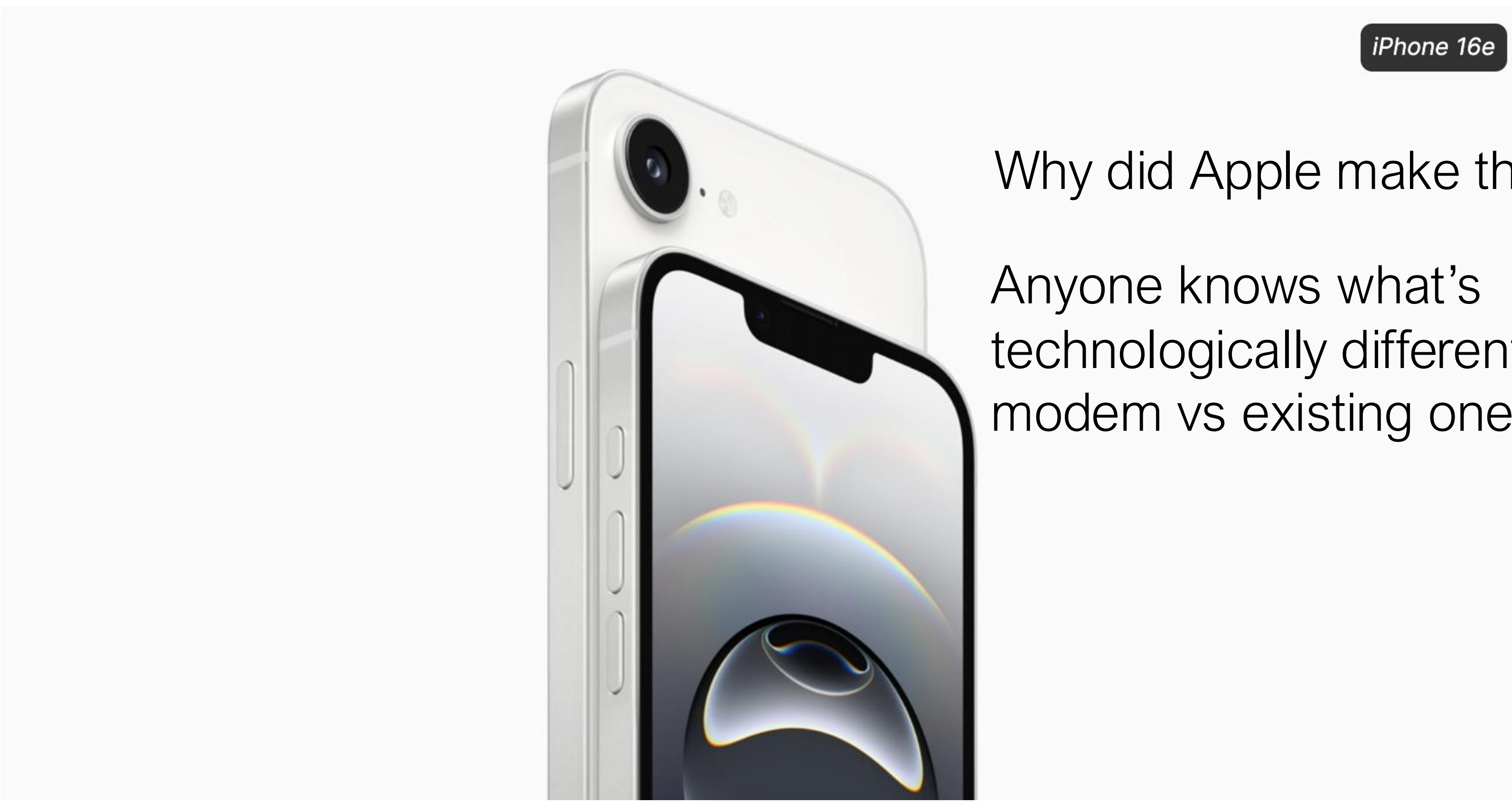
Lecture #6
Mesh Networks & Multi-Hop Routing

- Pset 1 due March 6
- Laptops/iPads are fine if you are taking notes for the class (but not for other work)

Today in IoT

Apple ends its Qualcomm dependency with the new C1 modem chip

Andrew Orr | Feb 21, 2025



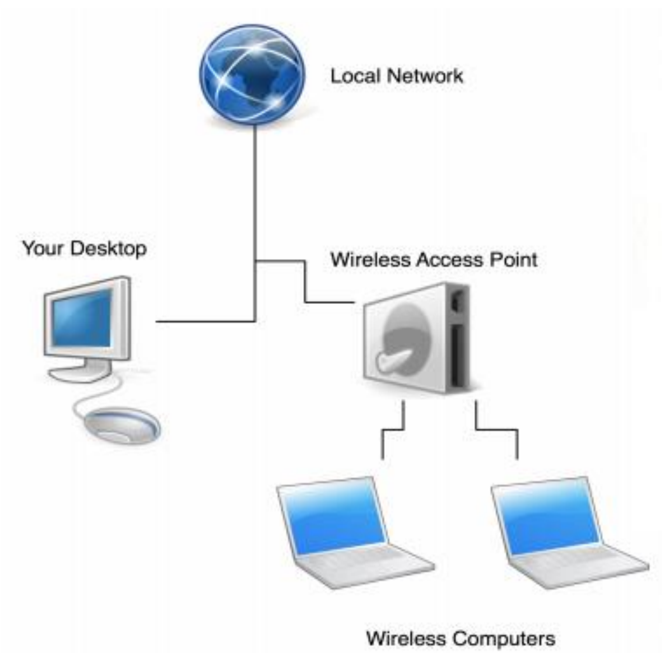
Why did Apple make this move?

Anyone knows what's technologically different about this modem vs existing ones?

Wireless Network Architectures

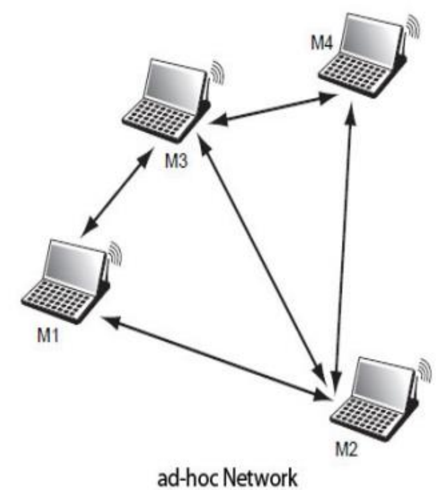
There are 3 kinds of wireless network architectures

Access Network



Device-to-device

Ad Hoc Network



e.g., WiFi, cellular

e.g., Bluetooth

e.g., leverage P2P to reach internet (crises)

One-hop

Multi-hop

RoofNet

MIT Technology Review

Networking From the Rooftop

MIT researchers are developing new routing strategies for a wireless network that hops data in the roofs of the city.

by **Erico Guizzo** Aug 29, 2003

A few weeks ago, MIT graduate student Shan Sinha canceled his broadband Internet service. Now his Net connection comes through the chimney. From

7 YEARS AFTER ROOFNET, MIT AND CSAIL CHOOSE MERAKI FOR WIRELESS LAN

February 17, 2010
Posted by: @merakisimon
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Cisco Acquires Enterprise Wi-Fi Startup Meraki For $1.2 Billion In Cash

Josh Constine @joshconstine / 6:36 pm EST • November 18, 2012 Comment

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Volume 125 >> Issue 65 : Wednesday, February 1, 2006 PDF of This Issue

MIT and City Collaborate To Provide Free ...ess

Thibault
...EWS EDITOR

...n with MIT researchers may provide Cambridge with a free, city-wide, wireless internet service as early ...er. The project will rely on a mesh networking technology that allows individual computers to become ...oints, projecting the reach of the network beyond its original antennas.

...l of the project is to provide internet access to Cantabrigians who live in public housing, said Cambridge ...tion Officer Mary P. Hart, though the resulting infrastructure will have a far wider benefit for city

...chow '68, vice president for Information Services and Technology, said he expects the maximum speed ...k to be 54 megabits per second. The speed users experience will decline as more people access the

... although the level of internet service will not be known until the antennas are tested, users should be ...a browser and send e-mail, though they might not be able to send large pictures or view streaming

Single Path Routing

Represent the wireless network as a graph

- Two nodes have an edge if they can communicate (i.e., are within radio range)
- Each edge is labeled with a weight (where a smaller weight indicates a preferred edge)

Run shortest path algorithm on the graph (e.g., Dijkstra)

- Produce the minimum weight path between every pair of nodes

How do you pick the edge weights?

- i.e., what metric should shortest path minimize?

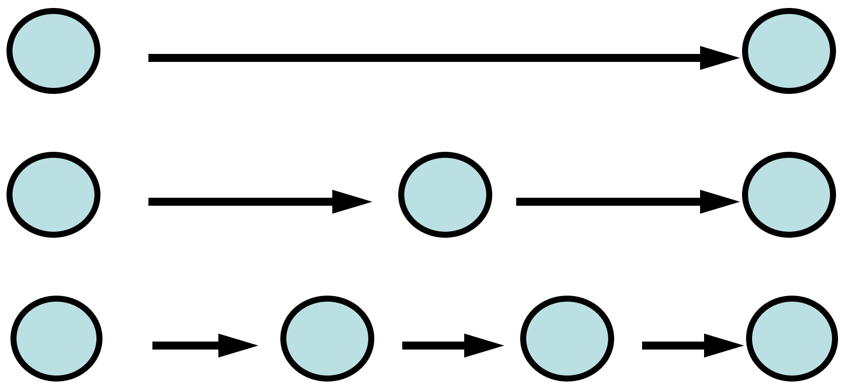
Focus of this lecture

Approach 1:

Assign all edges the same weight → Minimize number of hops

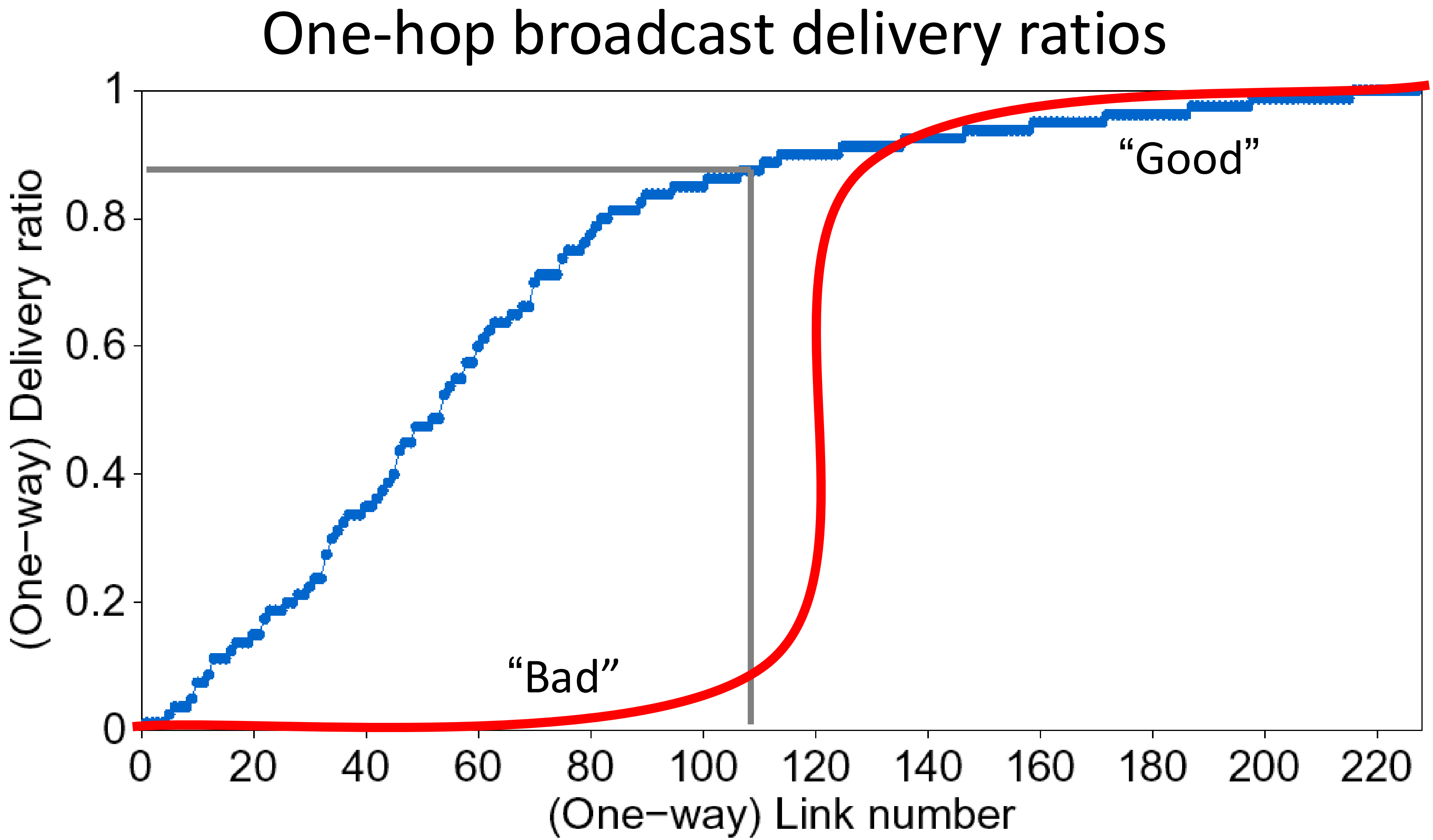
Reasoning:

- Links in route share radio spectrum
- Extra hops reduce throughput



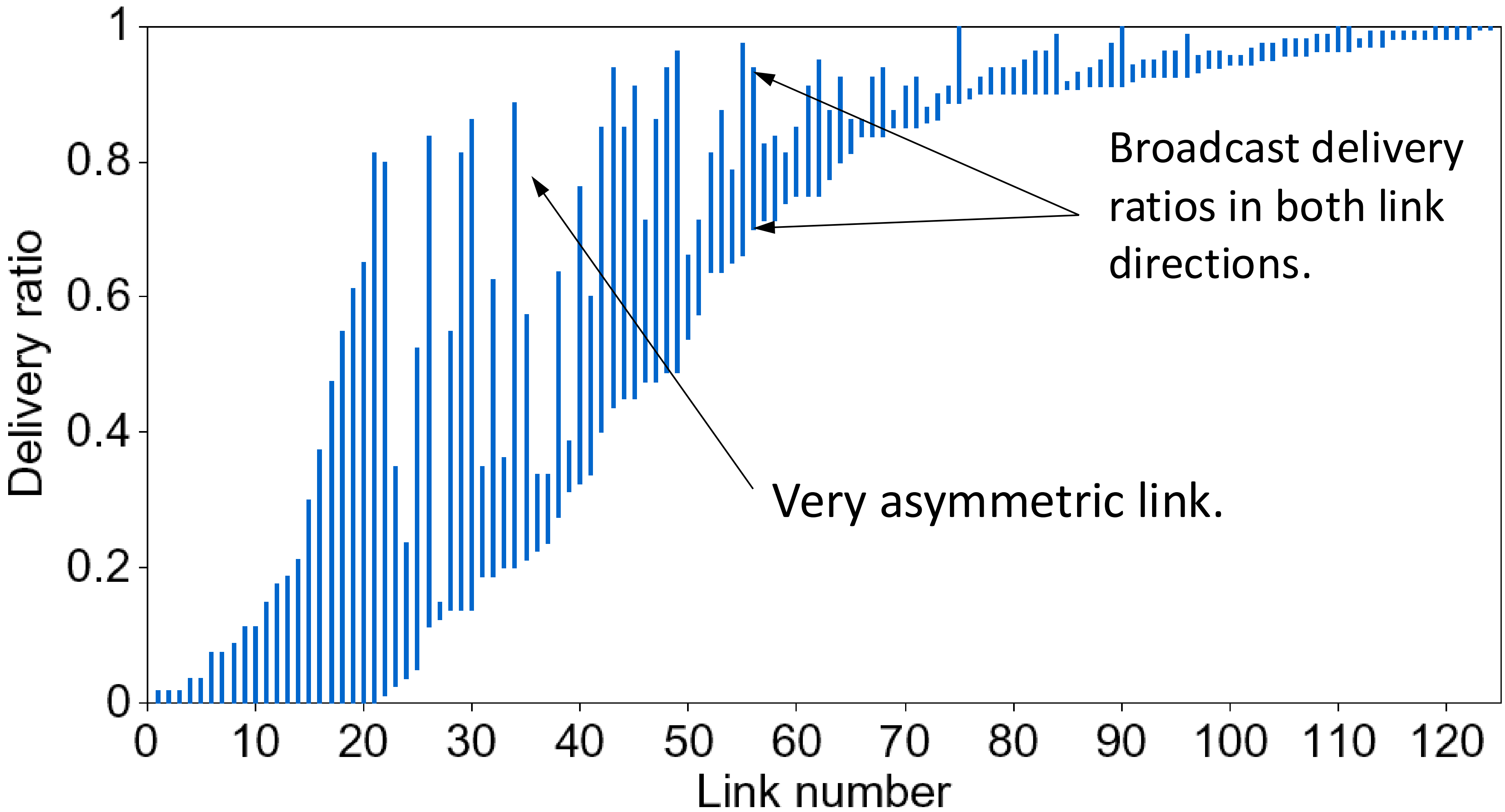
Pros? Cons?

Challenge: many links are lossy



Smooth link distribution complicates link classification.

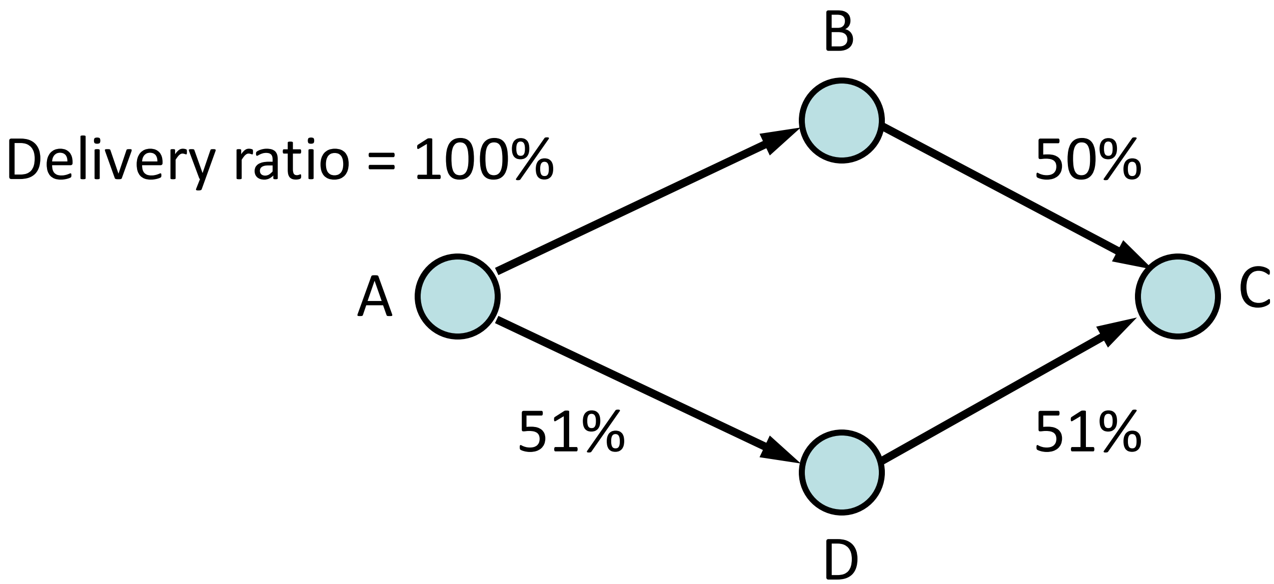
Challenge: links are lossy and asymmetric



Different links have different loss rates

Further, the loss rate may be different in each direction

Approach 2:
Maximize bottleneck throughput

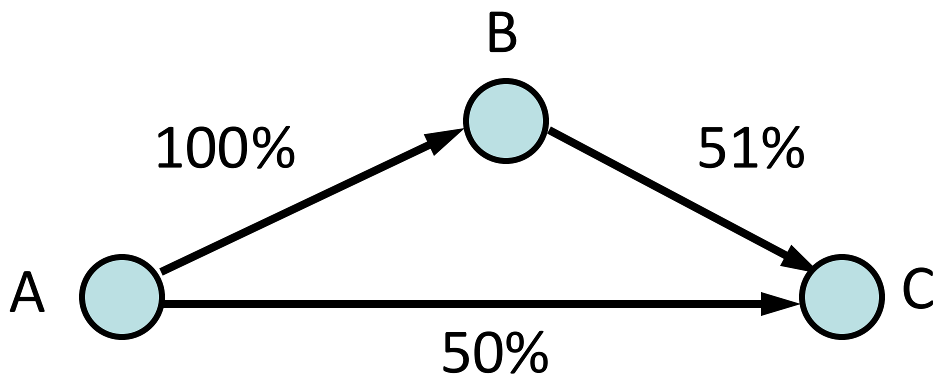


Bottleneck throughput:
- A-B-C = 50%
- A-D-C = <u>51%</u>

Actual throughput:
- A-B-C : ABBABBABB = <u>33%</u>
- A-D-C : AADDAADD = 25%

Pros? Cons?

Approach #3:
Maximize end-to-end delivery ratio



End-to-end delivery ratio:
- A-B-C = <u>51%</u>
- A-C = 50%

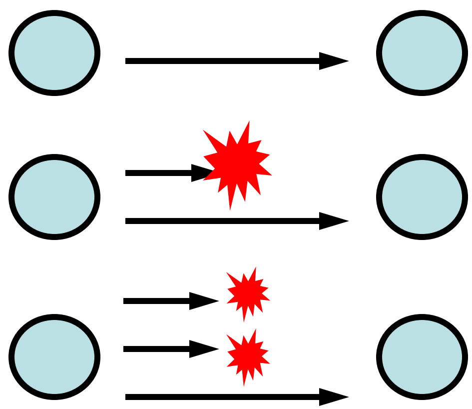
Actual throughput:
- A-B-C : ABBABBABB = 33%
- A-C : AAAAAAAA = <u>50%</u>

Pros? Cons?

Approach #4: Wireless routing metric: ETX

Minimize total transmissions per packet
(ETX, ‘Expected Transmission Count’)

Link throughput ≈ 1/ Link ETX



Delivery Ratio	Link ETX	Throughput
100%	1	100%
50%	2	50%
33%	3	33%

Calculating Link ETX

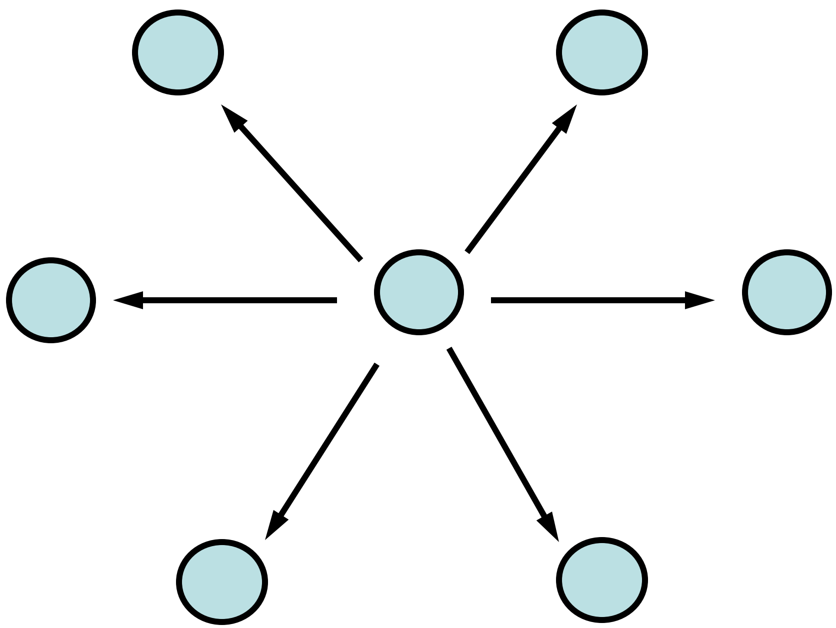
- Assuming 802.11 link-layer acknowledgments (ACKs) and retransmissions:
- P(TX success) = P(Data success) × P(ACK success)
- Link ETX = 1 / P(TX success)
  = 1 / [P(Data success) × P(ACK success)]
- Estimating link ETX:
- P(Data success) ≈ measured fwd delivery ratio r_{fwd}
- P(ACK success) ≈ measured rev delivery ratio r_{rev}
- Link ETX ≈ $1 / (r_{fwd} \times r_{rev})$

How can we measure delivery ratios?

- Each node broadcasts small link probes once per second
- Nodes remember probes received over past 10 seconds
- Reverse delivery ratios estimated as

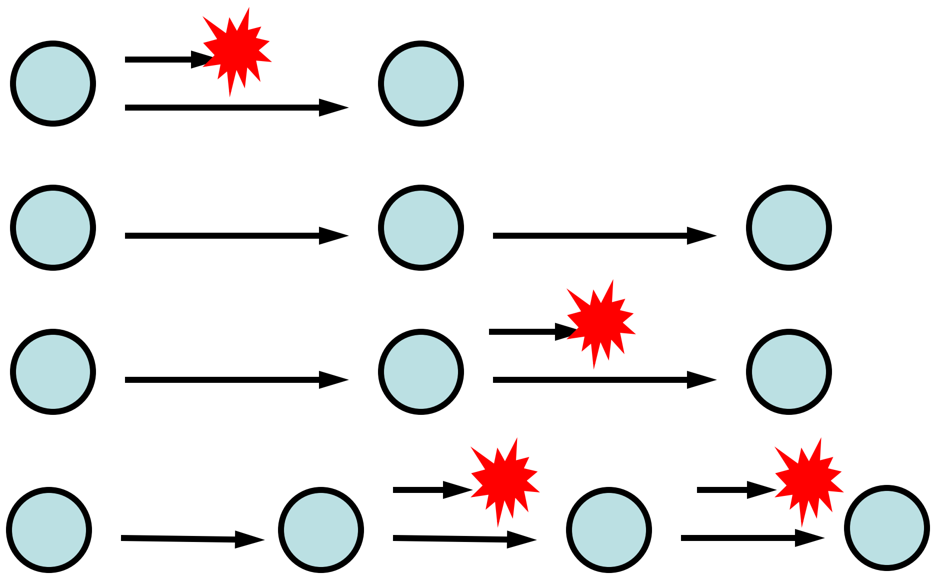
$$r_{rev} \approx \text{pkts received / pkts sent}$$

- Forward delivery ratios obtained from neighbors (piggybacked on probes)



Route ETX

Route ETX = Sum of link ETXs



Route ETX	Throughput
1	100%
2	50%
2	50%
3	33%
5	20%

ETX Pros?

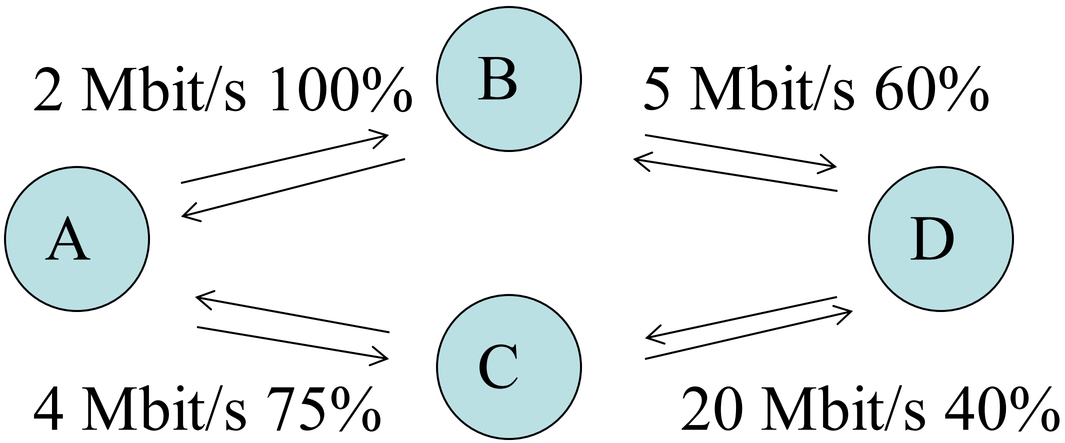
- ETX predicts throughput for short routes (1, 2, and 3 hops)
- ETX captures loss
- ETX captures asymmetry

ETX Caveats

- It is hard to measure link quality/loss
  - Changes as a function of load
  - Changes with time
- ETX ignores differences in bit-rate and packet size
- ETX ignores spatial re-use (i.e., assumes all links interfere)

How Can We Account to Different Bitrates?

(and different delivery ratios)



<u>Idea:</u> Take into account both the delivery rate and the **time** taken to transmit packet (i.e., time occupied on "air" by packet)

Assume pkt size = 20

ETT = ETX *(pkt_size/link-bit-rate)

Focus on 1-way

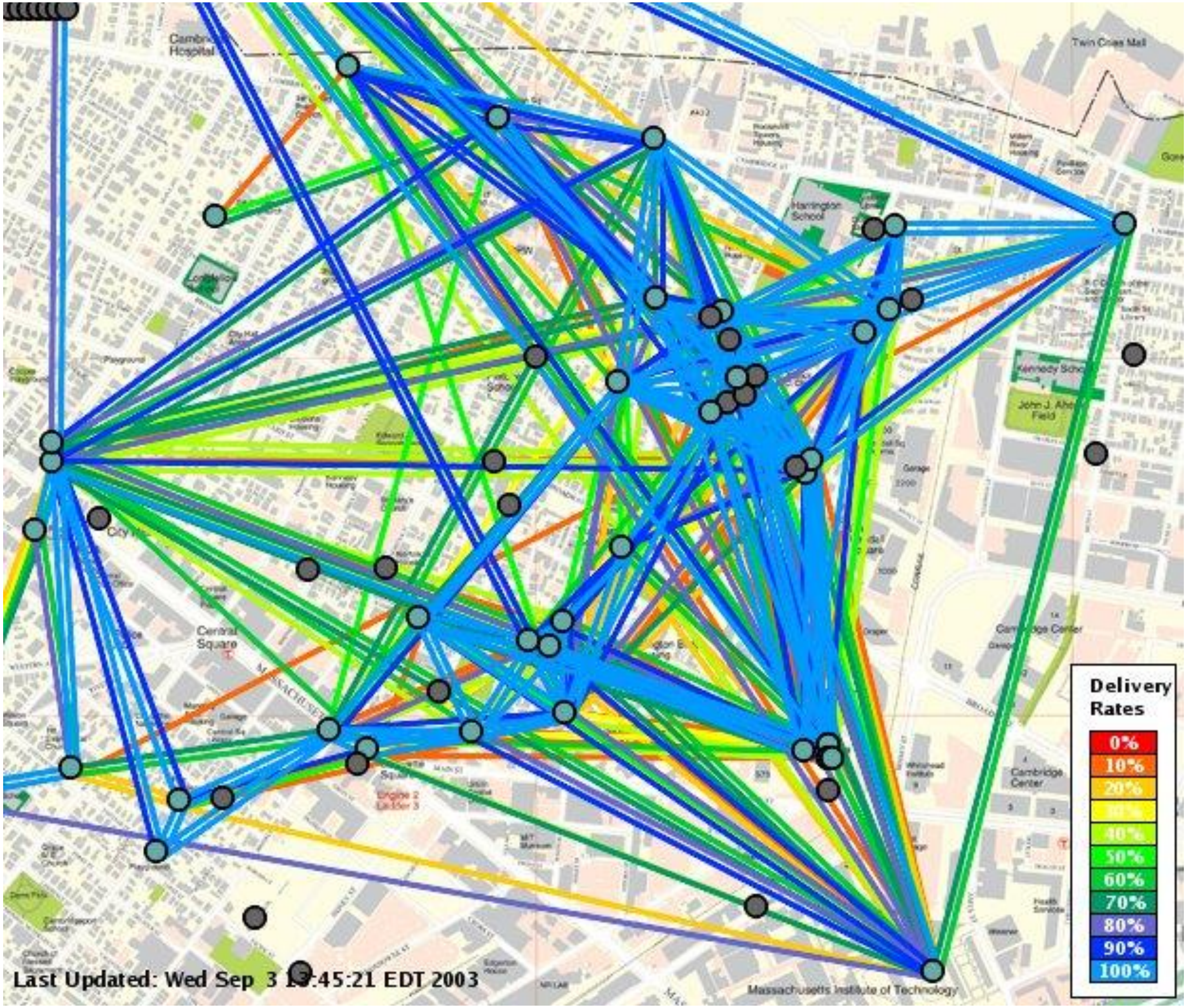
ABD: 1*10+ 5/3*4 = 50/3

ACD: 4/3*5 + 2/5*1 = 55/6

Caveats?

- Bitrate and delivery ratio are related
  - If Tx at higher rate, bitrate is lower
  - In fact, this problem led to the original rise of “information theory”
  - CS/EE -> rate adaptation based on “SNR”: signal-to-noise ratio
- Use multiple channels at the same time: each at different bitrate

MIT Roofnet



Delivery Rates
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Last Updated: Wed Sep 3 13:45:21 EDT 2003
Massachusetts Institute of Technology
Central Square
Harrington School
Cambridge Center

Where are mesh networks used today?

- Defense
- Electric car meters
- Home networks (e.g., Google WiFi, TP-link, etc.)
- Some satellite constellations (Iridium)
  - Will likely be replaced by LEO

Objectives of the Three Lectures Series

Learn the fundamentals, applications, and implications of
IoT connectivity technologies

1. What is the overall IoT system architecture?
2. What are the various classes of connectivity technologies? And how do we choose the "right" technology for a given application?
3. What are various routing architectures for wireless networks & IoT systems?
4. How does energy impact IoT device design? And how do batteryless IoT systems work?

next lecture