This lecture

- BLE
- IEEE 802.15.4 (Zigbee)
- Link Layer and collection tree protocol
- 6LoWPAN and RPL

Home and Building IoT Applications

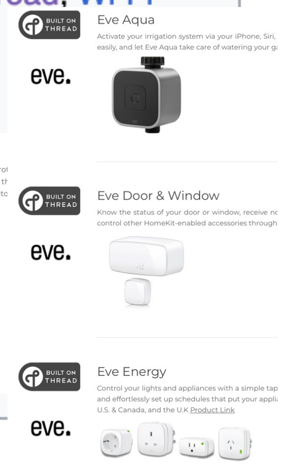
- Internet connectivity
- Multi-PC connectivity
- Audio/video networking
- Home automation
  - https://www.youtube.com/watch?v=kuWhtkv5Qbc&feature=youtu.be
- Energy conservation
- Security
- https://www.threadgroup.org/What-is-Thread/Thread-Benefits#certifiedproducts

Matter

Matter smart home connectivity standard

matter

Status	Published[1]
Year started	December 18, 2019; 3 years ago
First published	October 4, 2022; 7 months ago
Latest version	1.1 18 May 2023
Committee	Connectivity Standards Alliance
Authors	The connectivity standards alliance and Open source contributors
Base standards	Internet Protocol (IP)
Related standards	Zigbee, Z-Wave, Thread, Wi-Fi
Domain	Smart home
Licen	
Webs	

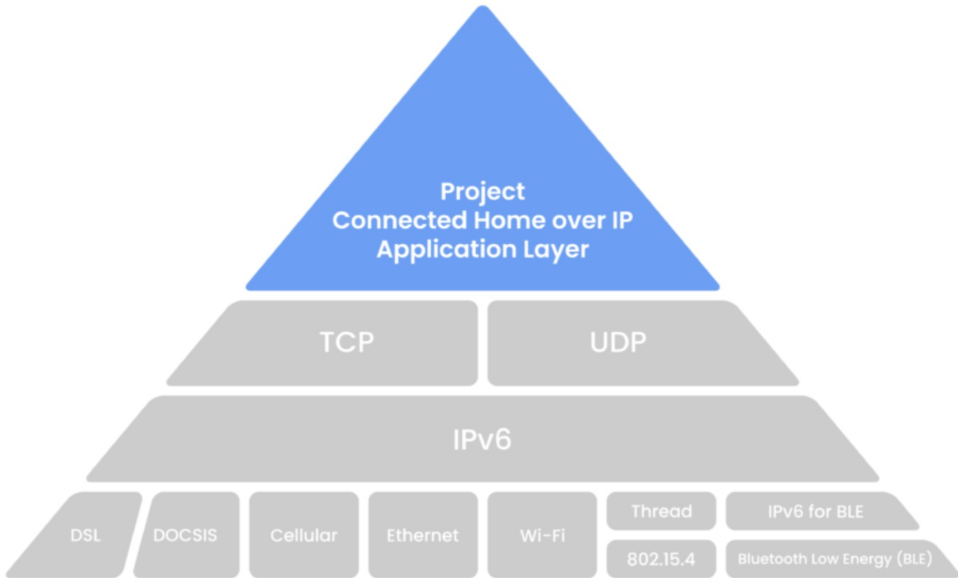


IEEE 802.15.4

- IEEE standard for low-rate WPAN applications
- Goals: low-to-medium bit rates, moderate delays without too stringent guarantee requirements, low energy consumption
- Physical layer
  - 20 kbps over 1 channel @ 868-868.6 MHz
  - 40 kbps over 10 channels @ 905 – 928 MHz
  - 250 kbps over 16 channels @ 2.4 GHz
- MAC protocol
  - Single channel at any one time
  - Combines contention-based and schedule-based schemes
  - Asymmetric: nodes can assume different roles

Motivation

- Personal area network requirements
  - Low Power Consumption
  - Minimal Installation Cost
  - Low Overall Cost
- Competing technologies
  - Wired
  - 802.11
  - Bluetooth (LE)



High-Level Characteristics

Property	Range
Raw data rate	868 MHz: 20 kb/s; 915 MHz: 40 kb/s; 2.4 GHz: 250 kb/s
Range	10–20 m
Latency	Down to 15 ms
Channels	868/915 MHz: 11 channels 2.4 GHz: 16 channels
Frequency band	Two PHYs: 868 MHz/915 MHz and 2.4 GHz
Addressing	Short 8-bit or 64-bit IEEE
Channel access	CSMA-CA and slotted CSMA-CA
Temperature	Industrial temperature range –40 to +85 C

Table 1. *Summary of high-level characteristics. CSMA-CA: carrier sense multiple access with collision avoidance.*

Physical Layer

- Two Potential Physical Layers
  - 868/915Mhz
  - 2.4Ghz
  - Same Packet Structure
- 27 Frequency Channels Total
- Dynamic Channel Selection left to network layer

Channel structure

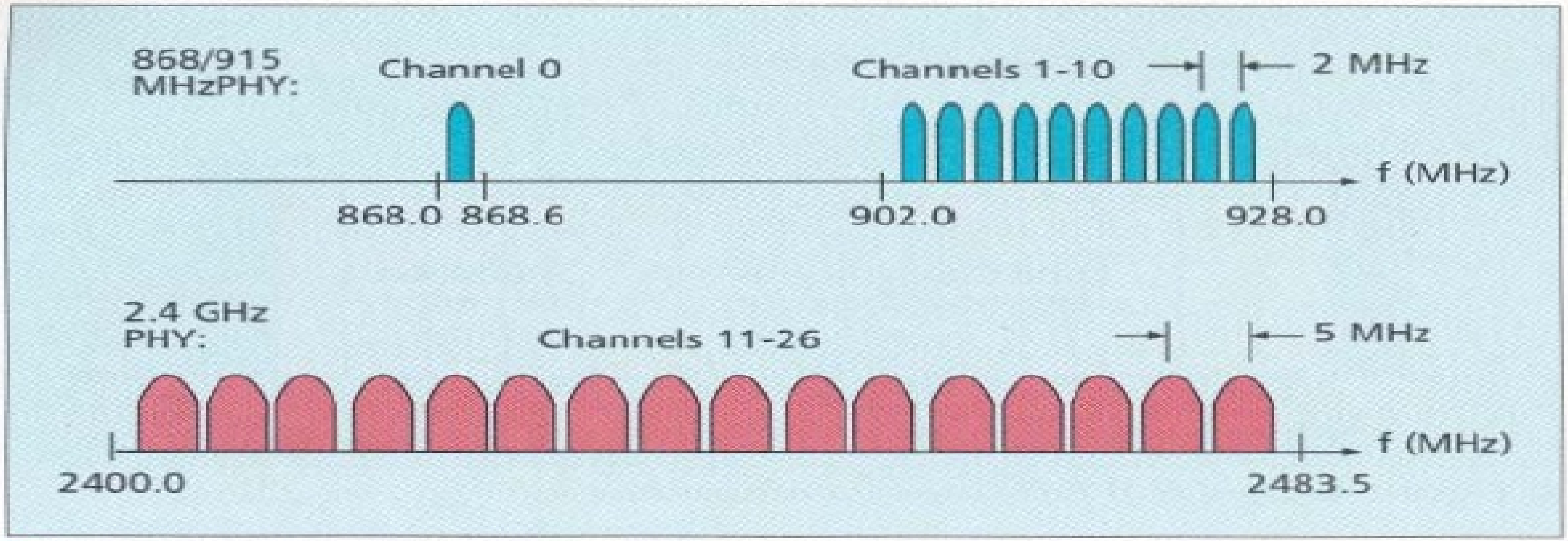


Figure 5. *The IEEE 802.15.4 channel structure.*

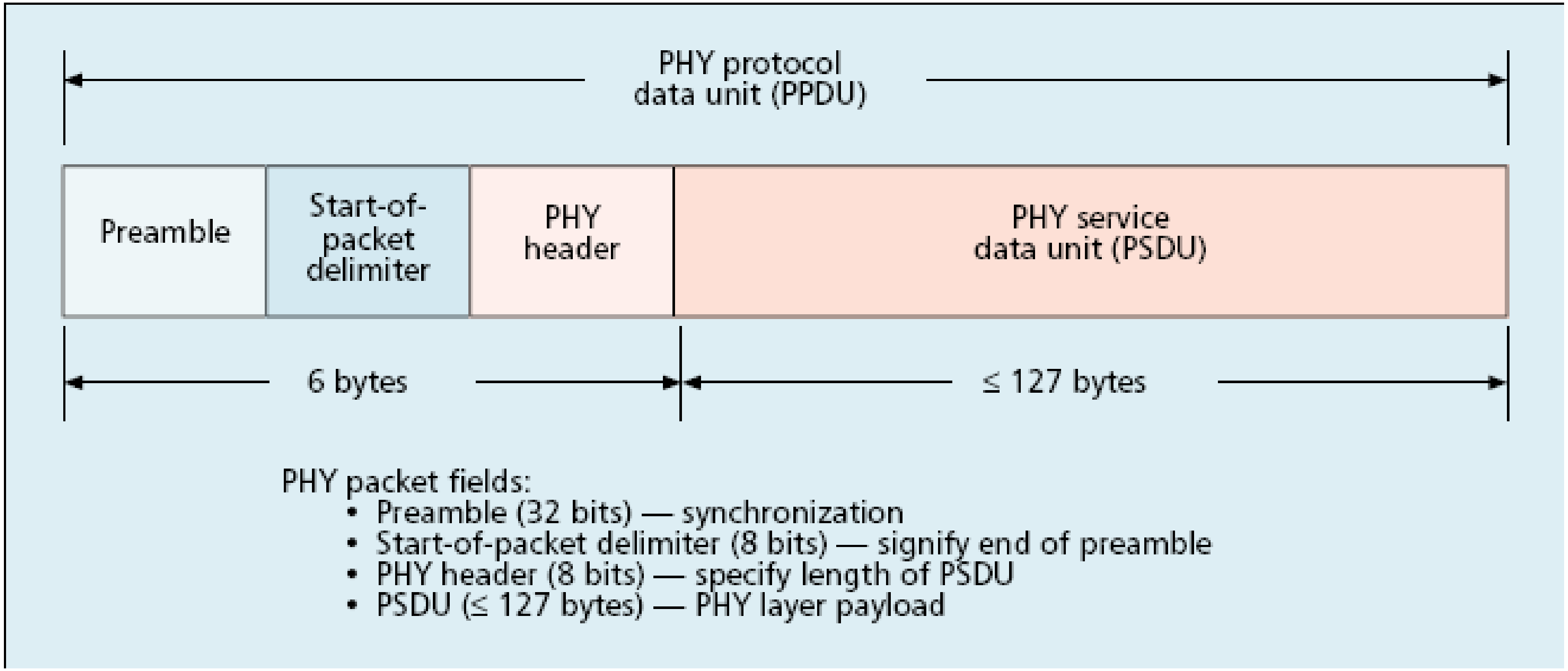
Channel number	Channel center frequency (MHz)
$k = 0$	868.3
$k = 1, 2, \ldots, 10$	$906 + 2(k - 1)$
$k = 11, 12, \ldots, 26$	$2405 + 5(k - 11)$

Table 2. *IEEE 802.15.4 channel frequencies.*

Other Physical Layer Features

- Sensitivity and Range
  - 868/915 → -92 dBm
  - 2.4 → -85 dBm
  - 10-20m typical range

Physical Layer Packet Structure



Device Classes

- Full Function Devices (FFD)
  - Any topology
  - PAN coordinator capable
  - Talks to any other device
  - Implements complete protocol stack

- Reduced Function Device (RFD)
  - Reduced protocol stack
  - Very simple implementation
  - Cannot become a PAN coordinator
  - Limited to leaf nodes in more complex topologies

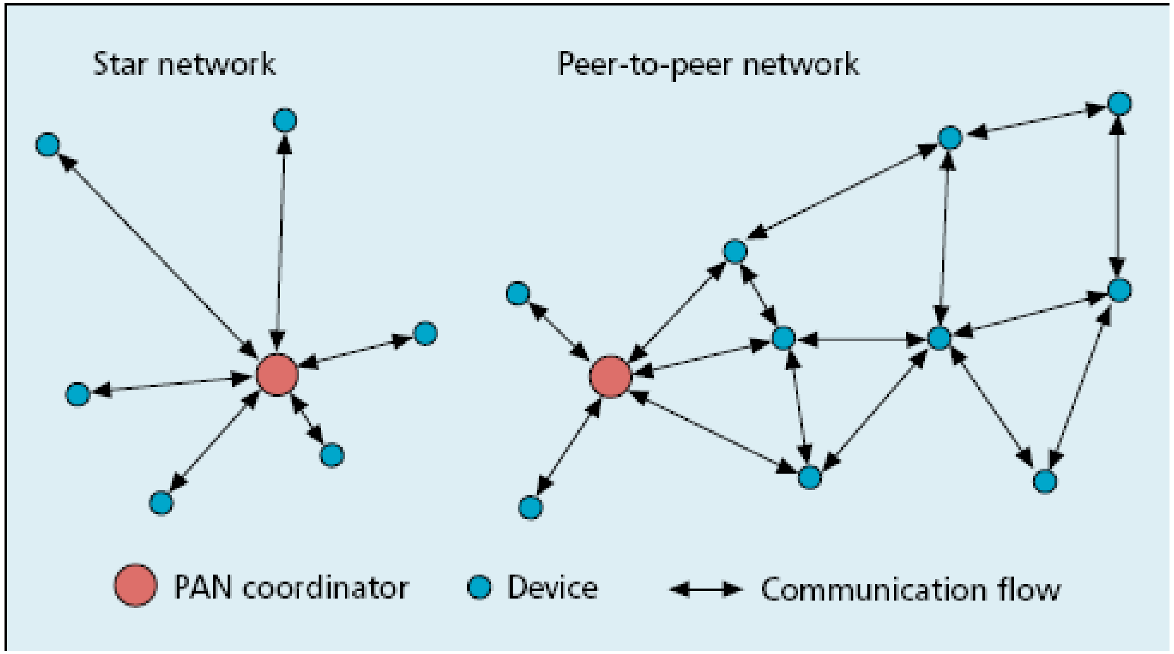
Device Definitions

- Network Device
  - An RFD or FFD implementation containing an IEEE 802.15.4 medium access control and physical interface to the wireless medium
- Coordinator
  - An FFD with network device functionality that provides coordination and other services to the network
- PAN Coordinator
  - A coordinator that is the principal controller of the PAN. A network has exactly one PAN coordinator.

Network Layer Guidelines

- 802.15.4 Specification does not address Network Layer
- Expected to be self-organizing and self-maintaining to minimize cost to user
- Two Network Topologies Supported:
  - Star Topologies
  - Peer-to-Peer Topologies

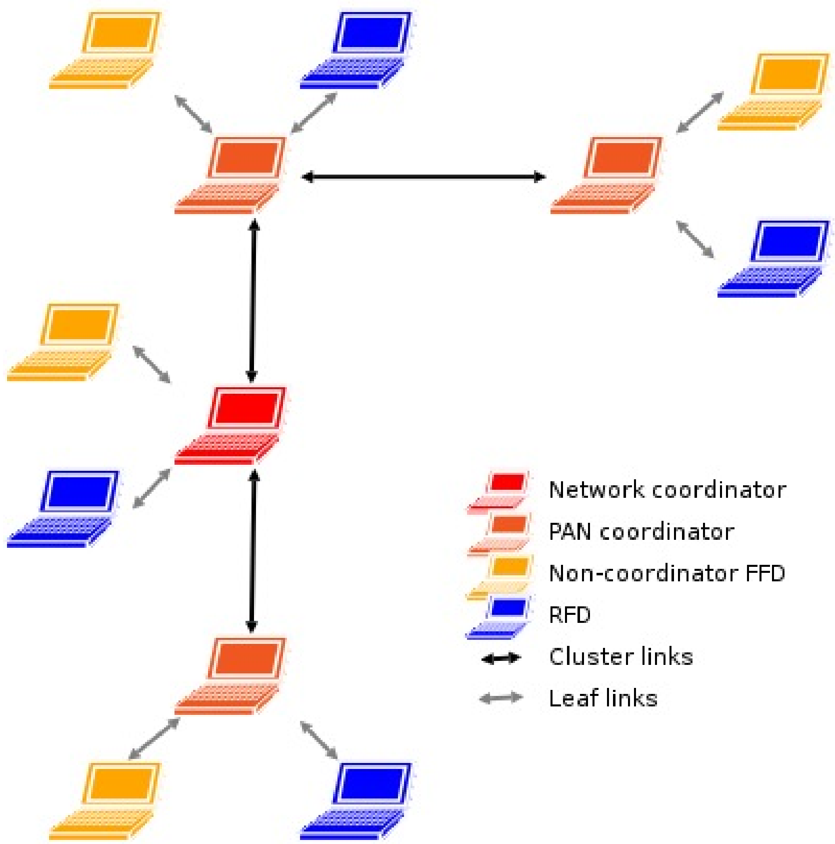
Topology Formations



Star Topology
- All nodes communicate via PAN coordinator
- Leaf nodes – combination of FFD and RFD devices

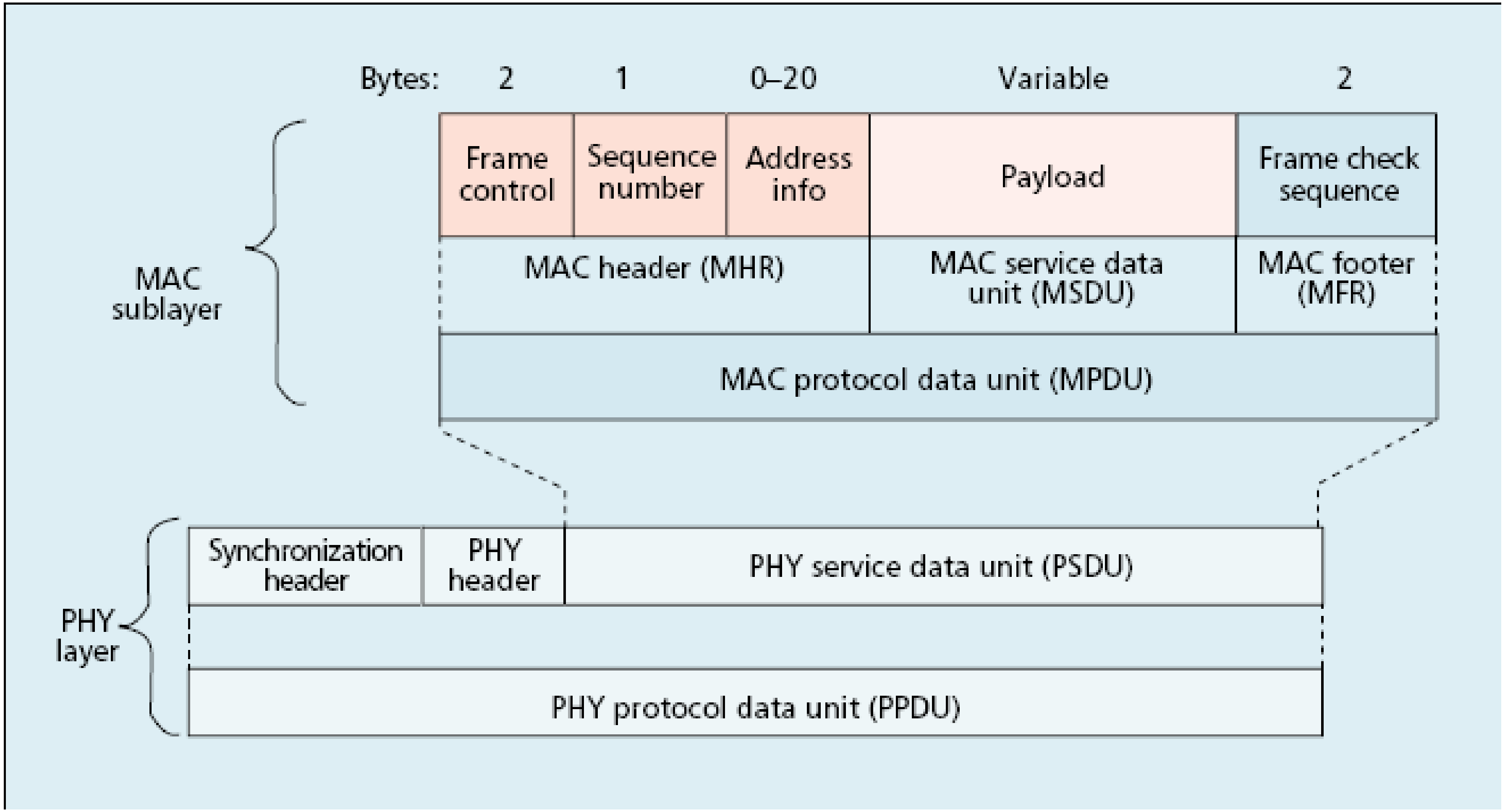
Peer to Peer Topology
- Extension of star topology
- Nodes can communicate via PAN coordinator and also additional point-to-point links

Cluster Tree Topology



- Leaf nodes connect to a network of coordinators (FFDs)
- One of the coordinators serves as the PAN
- Clustered start topologies are an in important case (e.g., each hotel room forms a star in a HVAC system)

MAC Frame Format



Frame Structure

Bytes:2	1	0/2	0/2/8	0/2	0/2/8	variable	2
Frame control	Sequence number	Destination PAN identifier	Destination address	Source PAN identifier	Source address	Frame payload	Frame check sequence
		Addressing fields					
MAC header						**MAC payload**	**MAC footer**

Bits: 0-2	3	4	5	6	7-9	10-11	12-13	14-15
Frame type	Sequrity enabled	Frame pending	Ack. Req.	Intra PAN	Reserved	Dest. addressing mode	Reserved	Source addressing mode

- IEEE 64-bit extended addresses (globally unique)
- 16-bit “short” addresses (unique within a PAN)
- Optional 16-bit source/destination PAN identifiers
- Max. frame size 127 bytes, max-frame header: 25 bytes

Frame types

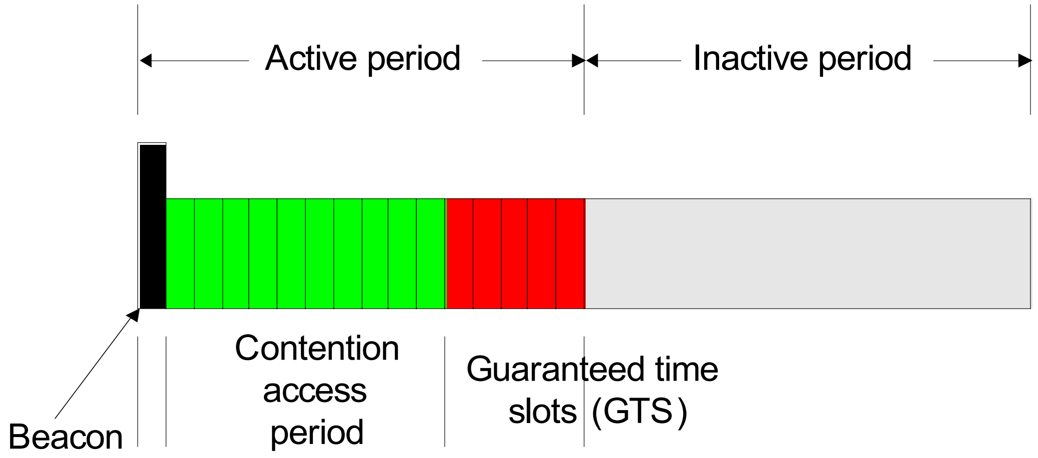
- Beacon Frames
  - Broadcast by the coordinator to organize the network
- Command Frames
  - Used for association, disassociation, data and beacon requests, conflict notification, ….
- Data Frames
  - Carry user data
- Acknowledgement Frames
  - Acknowledges successful data transmission (if requested)

CSMA/CA Review

- Carrier Sense Multiple Access/Collision Avoidance
  - First wait until the channel is idle
  - Once the channel is free, start sending the data frame after some random back-off interval
  - Receiver acknowledges the correct reception of a data frame
  - If the sender does not receive an acknowledgement, retry the data transmission

IEEE 802.15.4 MAC overview

- Beacon-mode superframe structure
  - Time between beacons divided in 16 time slots
  - GTS assigned to devices upon request
    - can be used to provide bandwidth guarantees
  - Contention-free period and duration of superframe announced in beacon



Additional MAC Features

- Channel Access Mediums
  - Slotted CSMA-CA (beacon mode)
  - Unslotted CSMA-CA
- Acknowledgements
- Security

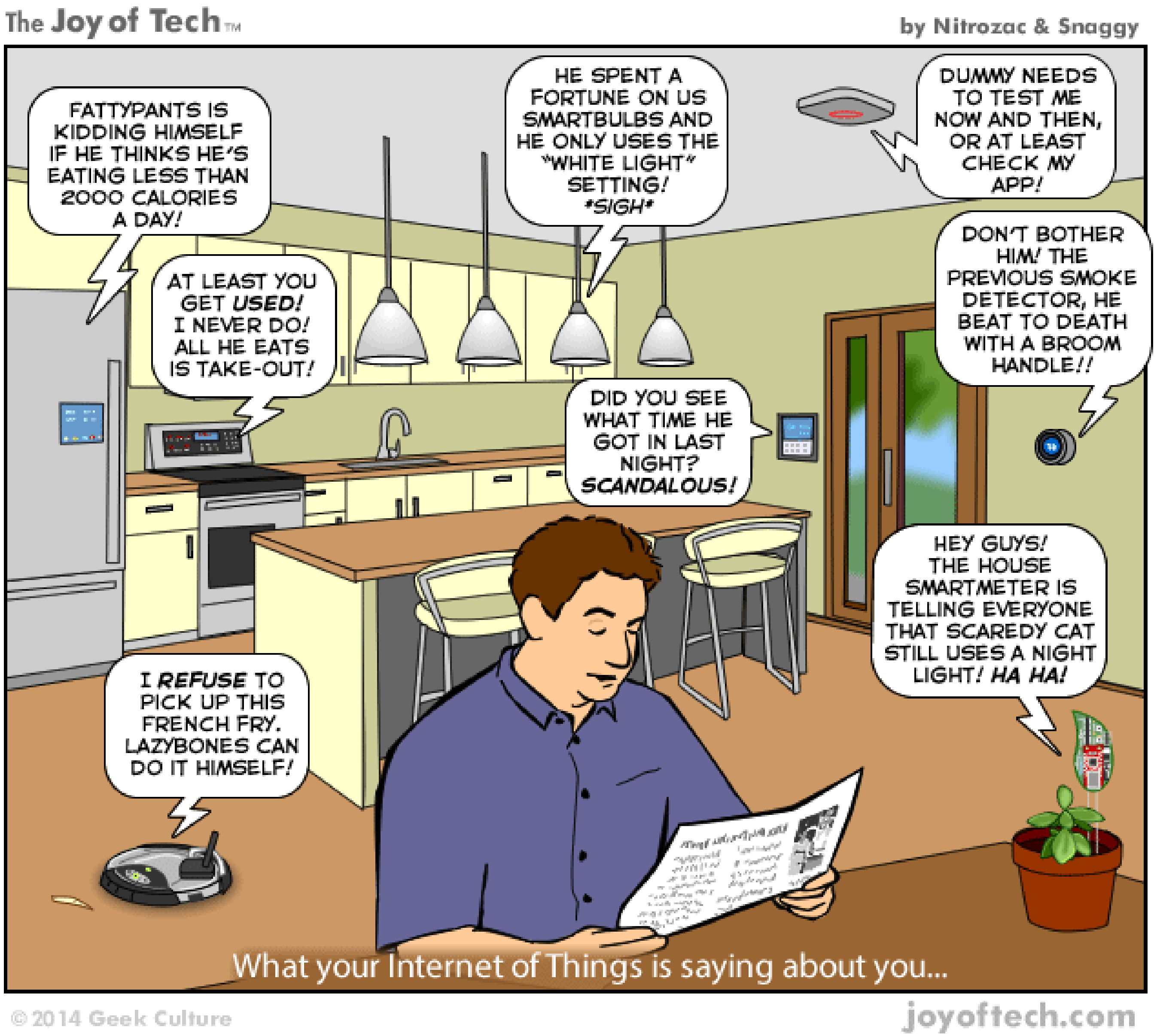
Security Suite	Description
Null	No security (default)
AES-CTR	Encryption only, CTR Mode
AES-CBC-MAC-128	128 bit MAC
AES-CBC-MAC-64	64 bit MAC
AES-CBC-MAC-32	32 bit MAC
AES-CCM-128	Encryption and 128 bit MAC
AES-CCM-64	Encryption and 64 bit MAC
AES-CCM-32	Encryption and 32 bit MAC

Link layer: Introduction

- Link layer sits above the MAC layer
- Need to know: Comparing today's wireless networks and wired networks, the bit error rate in a wireless network is higher
  - Due to interference and its more "open" environment, wireless transmissions are more susceptible to error
  - Wired transmissions are shielded from external interference and can have a far higher signal-to-noise ratio

Link layer: Main functions

- Error control
  - Automatic Repeat reQuest (ARQ)
    - Resend packet if it is received in error
  - Forward Error Correction
    - Correct small number of bit errors
- Framing
  - Determining an optimal frame size
- Link management
  - This is specific for wireless networks


The Joy of Tech™
by Nitrozac & Snaggy
FATTYPANTS IS KIDDING HIMSELF IF HE THINKS HE'S EATING LESS THAN 2000 CALORIES A DAY!
AT LEAST YOU GET USED! I NEVER DO! ALL HE EATS IS TAKE-OUT!
HE SPENT A FORTUNE ON US SMARTBULBS AND HE ONLY USES THE "WHITE LIGHT" SETTING! *SIGH*
DUMMY NEEDS TO TEST ME NOW AND THEN, OR AT LEAST CHECK MY APP!
DON'T BOTHER HIM! THE PREVIOUS SMOKE DETECTOR, HE BEAT TO DEATH WITH A BROOM HANDLE!!
DID YOU SEE WHAT TIME HE GOT IN LAST NIGHT? SCANDALOUS!
HEY GUYS! THE HOUSE SMARTMETER IS TELLING EVERYONE THAT SCAREDY CAT STILL USES A NIGHT LIGHT! HA HA!
I REFUSE TO PICK UP THIS FRENCH FRY. LAZYBONES CAN DO IT HIMSELF!
What your Internet of Things is saying about you...
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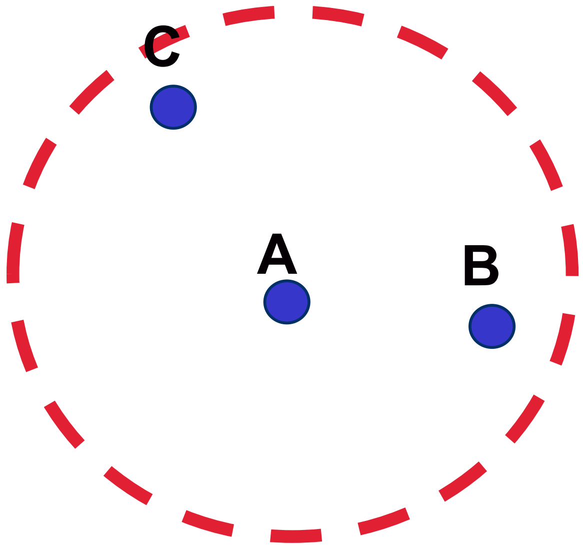
Collection tree protocol

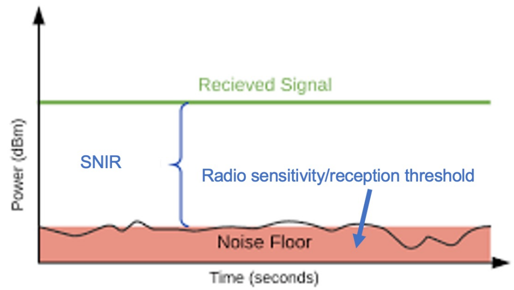
- Based on the following conference article: "Taming the underlying challenges of reliable multi-hop routing in sensor networks"
  - Huge impact on RPL "Ripple", Thread/Matter
- We begin by discussing about **link quality estimation**

Simplified view on links

- Simplified/deterministic view of packet reception
  - If the Signal to Noise and Interference (SNIR) of a packet is above the reception threshold, then the packet is received correctly
  - If Node B is within the transmission range of Node A, then Node B will always receive the packet correctly

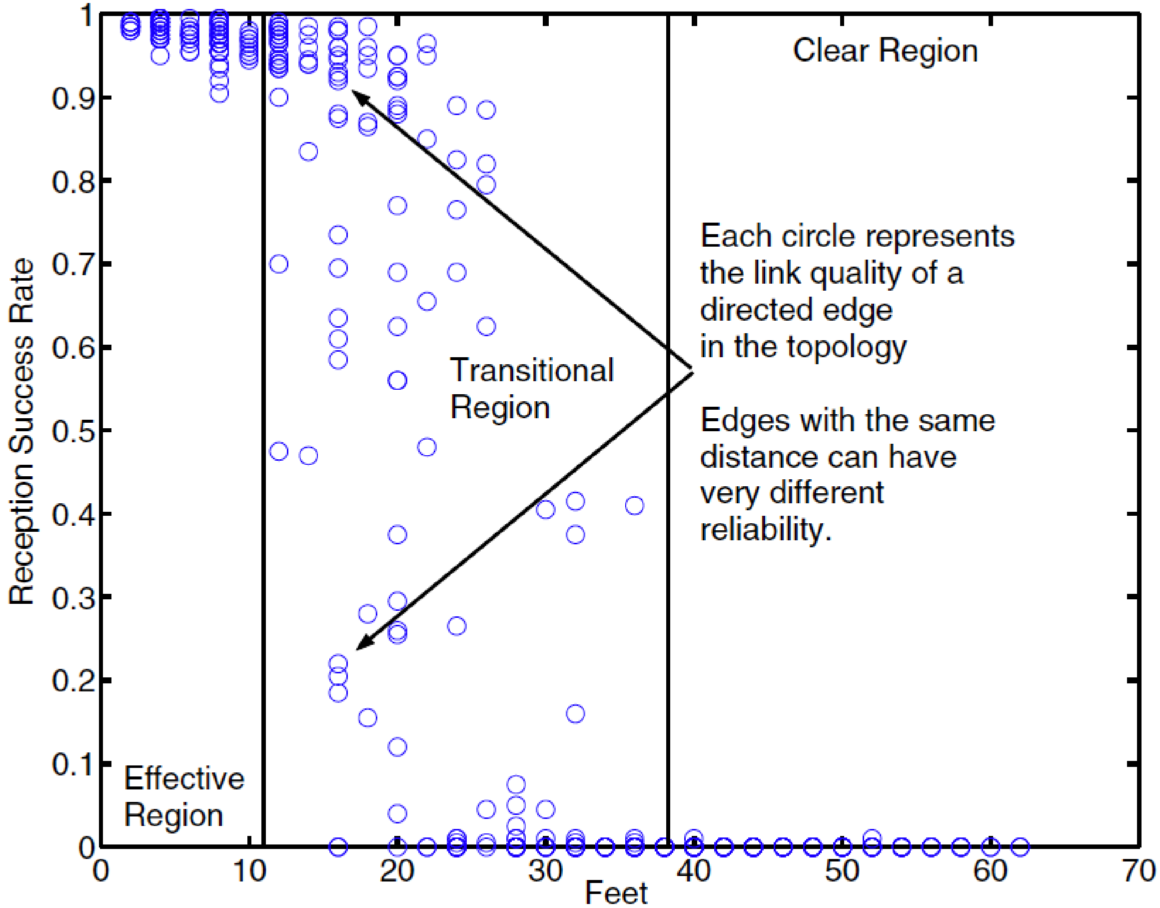


- Simplified or binary view on links
  - If Node B is within the transmission range of Node A, the link connecting A and B always exists
  - Circular reception model



Experimental link quality (1)

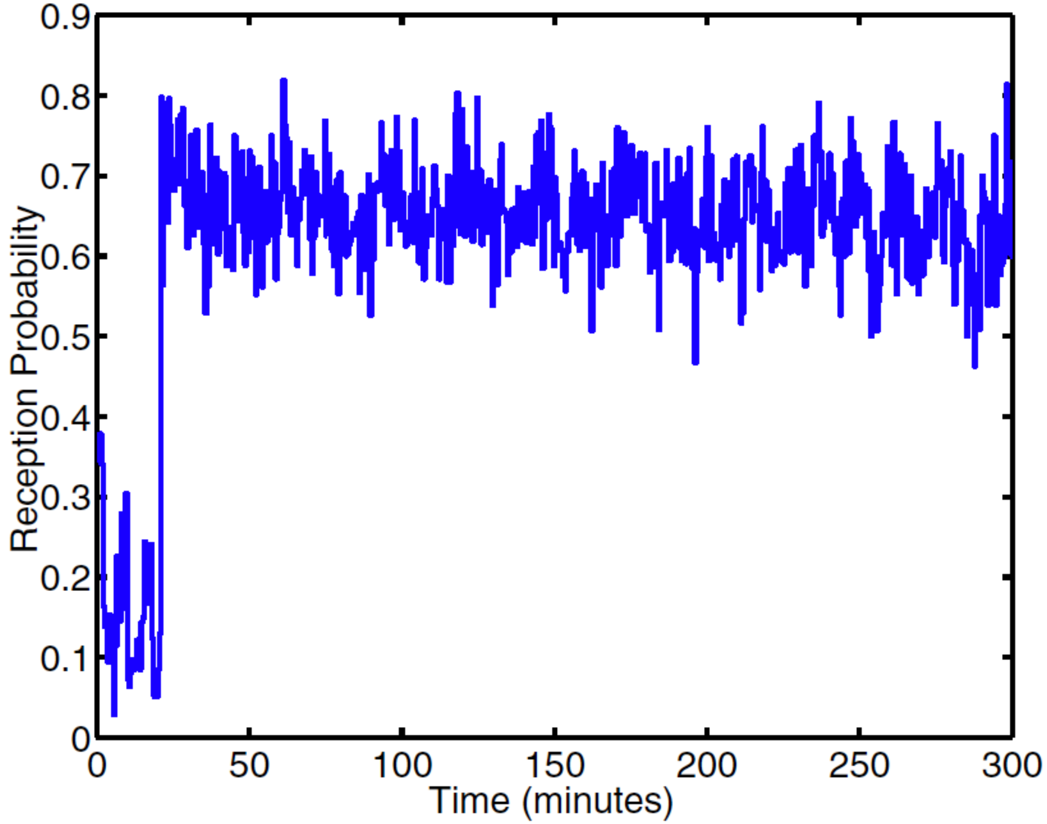
- PER = packet error rate
- ***Effective region***: PER consistently < 10%
- ***Transitional region:*** anything in between, with large variation for nodes at same distance
- ***Poor region***: PER well beyond 90%



Reception probability of al links in a network with a line topology (nodes are 2 feet apart)

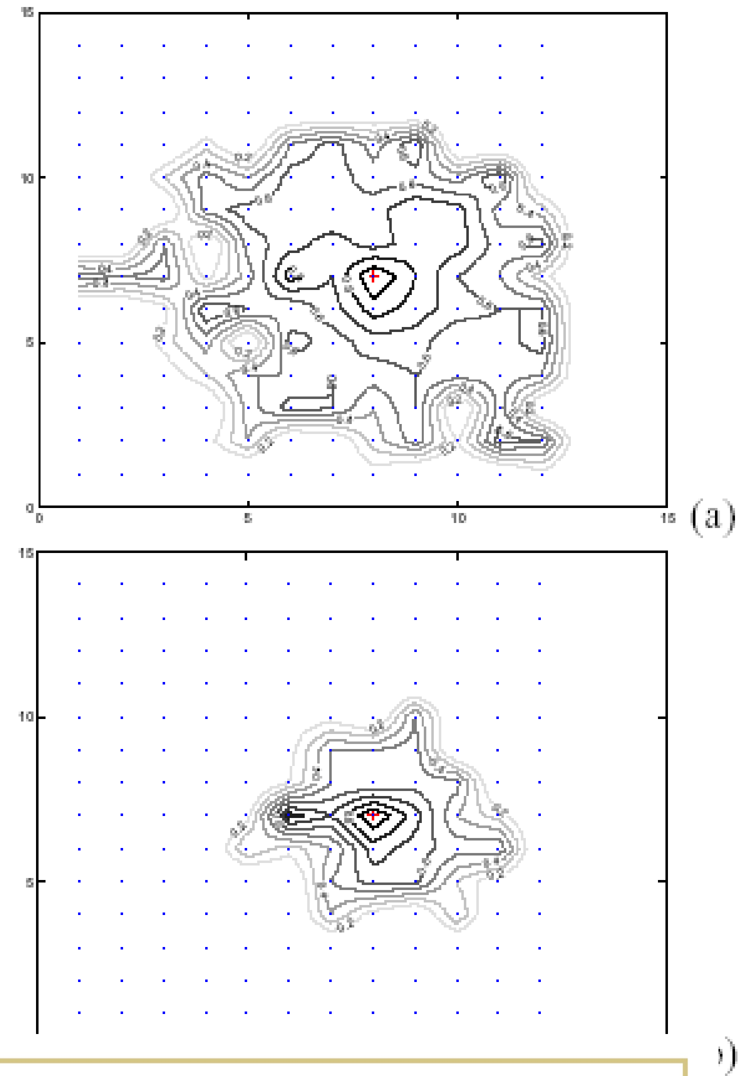
Experimental link quality (2)

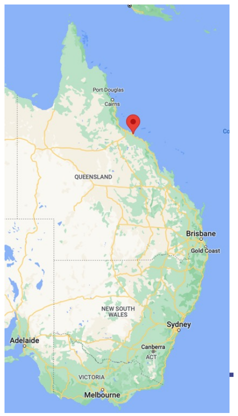
The packet loss probability of each link can change with time



Experimental link quality (3)

- Simple, circular shape of "region of communication" – not realistic
- Instead:
  - Correlation between distance and loss rate is weak; iso-loss-lines are not circular but irregular
  - Asymmetric links are relatively frequent (up to 15%)
    - Asymmetric link: Node A can hear Node B but not the other way
  - Significant short-term PER variations even for stationary nodes





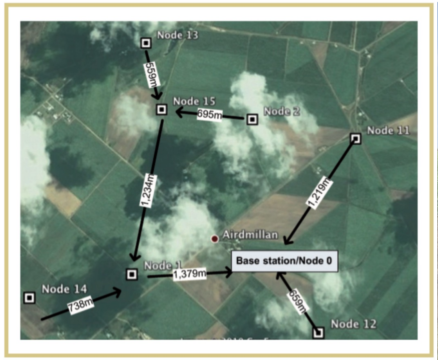
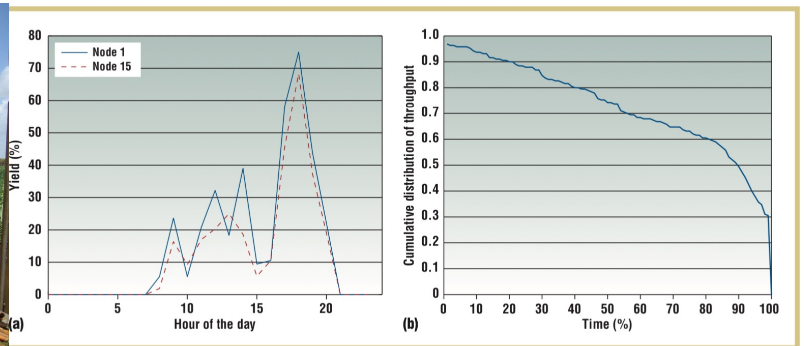


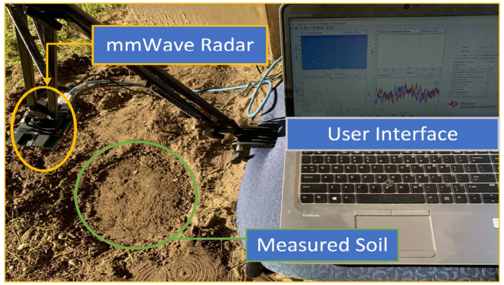
Figure 2. The most common network topology superimposed on a satellite image. The mean transmission range was 855 meters. (Source: GeoEye; used with permission.)



ure 6. Quality of communication links. (a) Daily temporal variation of yield for two nodes, computed during 20 to 26 May 7. (b) Cumulative distribution of Internet backlink throughput from 23 April to 23 November 2007.

Radio-based Sensing?

(a) (b)



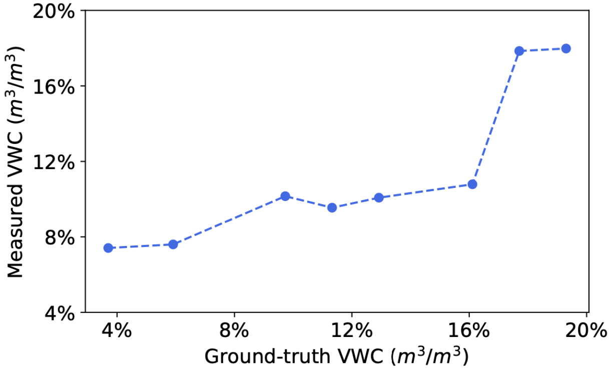
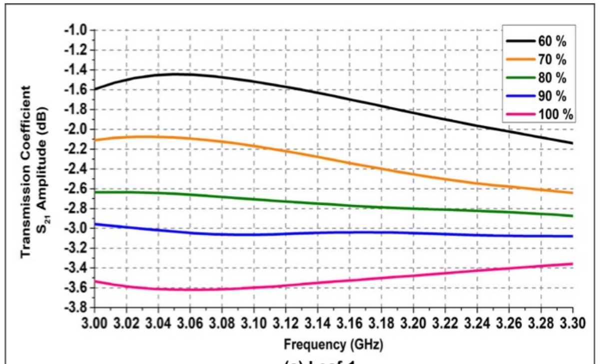


TABLE 1. Weight variation of camellia leaves with change in wetness.

Weight Percentage, P (%)	Weight of Leaf-1 (g)	Weight of Leaf -2 (g)	Weight of Leaf -3 (g)
100	1.07	0.96	1.06
90	0.963	0.864	0.954
80	0.856	0.768	0.848
70	0.75	0.672	0.742
60	0.642	0.576	0.636



(a) Leaf-1

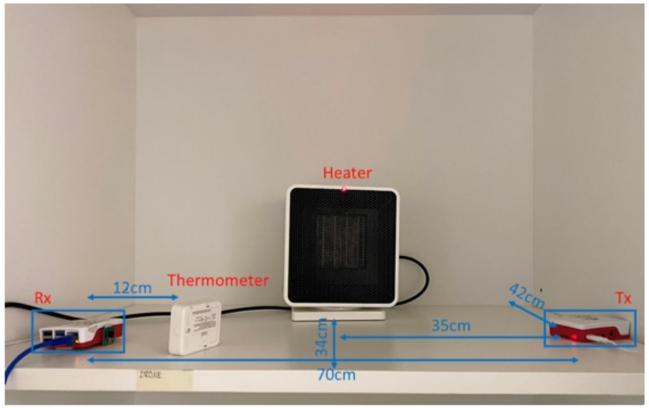


Fig. 2: Experimental setup in a closed cupboard

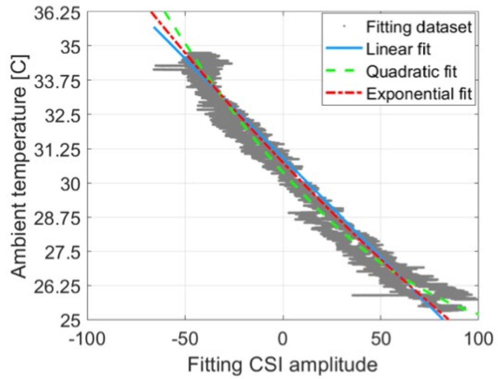


Fig. 8: Linear fit of CSI amplitude of subcarrier 22 and ambient temperature

True view on links

- Links should be viewed probabilistically
  - Packet reception is probabilistic
  - Packet reception depends on direction
  - The link quality can vary with time
- Implication:
  - Neighbour set of a node changes
    - Example: Node B can be a neighbour of Node A when the reception is good, but when the reception is bad, Node B ceases to be a neighbour of Node A

Link management

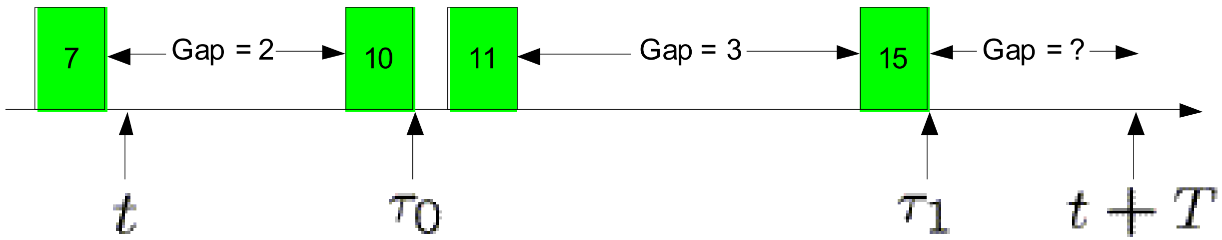
- Goal: a link should be "established" to neighbors that are *more or less* reachable
  - Problem: communication quality fluctuates, far away neighbors can be costly to talk to, error-prone, quality can only be estimated
- Establish a ***neighborhood table*** for each node
  - Partially automatically constructed by MAC protocols
- Since link quality changes with time, it must be estimated dynamically

Link estimation (1)

- Each node can estimate link quality by observing the number of successfully delivered packets out of the number of packets sent
- Two classes of methods
  - Active method: Active probes
    - Issue: Increases the amount of traffic
  - Passive method: Snooping
    - Issue: Can't tell the difference between a node not sending and the loss of all the packets from that node
- The estimated link quality can be used as cost metric for routing
- Good estimator should:
  - Precision – estimator should give the statistically correct result
  - Agility – estimator should react quickly to changes
  - Stability – estimator should not be influenced by short aberrations
  - Efficiency – small memory footprint and simple, lightweight computation

Link estimation (2)

- Method used in the paper
  - Snooping
  - Assumption: Each node sends periodic traffic
- Used WEMA (**Window mean** with **exponentially weighted moving average**) estimator



$$P_n = \alpha P_{n-1} + (1-\alpha)\frac{r_n}{r_n+f_n}$$

r_n: received packets in interval

f_n: packets identified as lost

Link estimation (3)

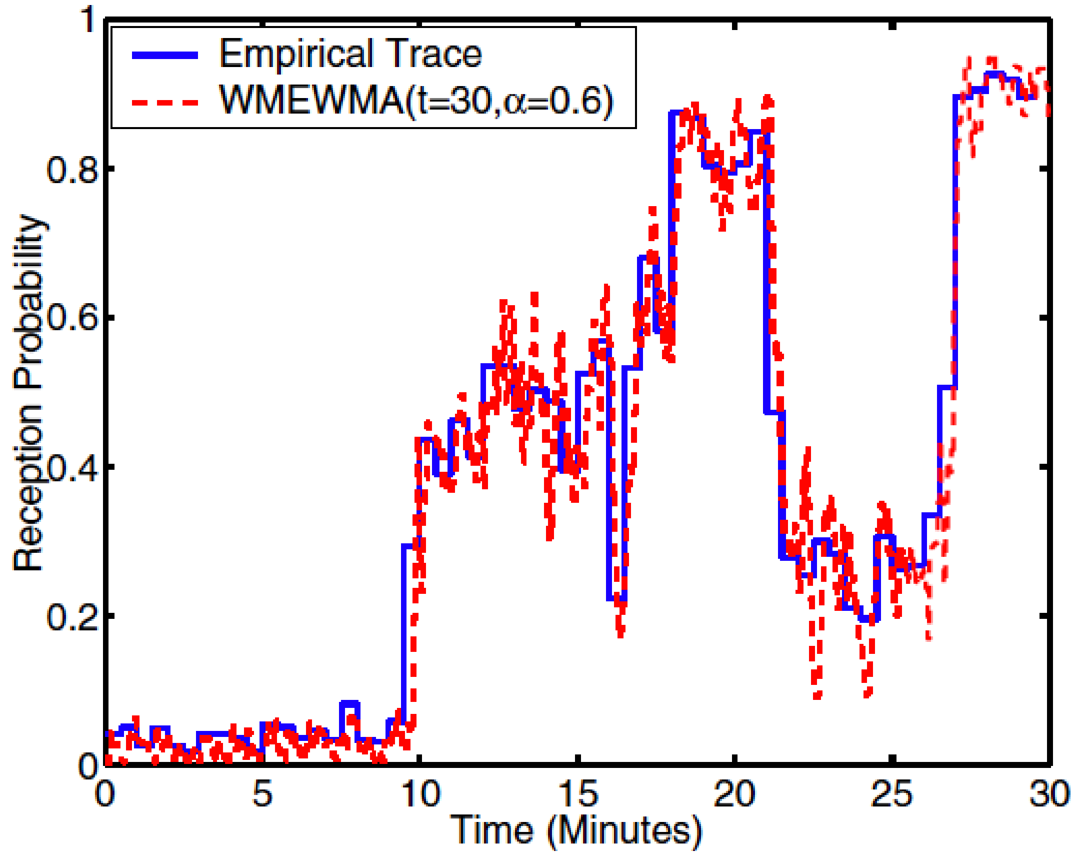


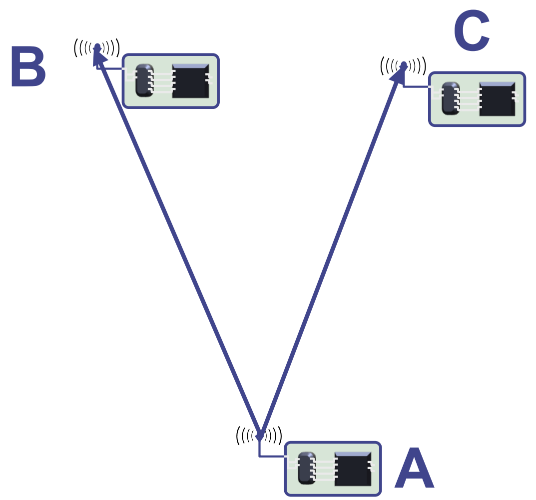
Figure 3: WMEWMA($t = 30, \alpha = 0.6$) with stable setting using empirical traces.

Neighbour table management

- Each node decides which neighbouring nodes should be in its neighbour table
- Size of neighbour table is limited: If the table is full and the node wants to insert a new neighbour, it needs to evict an existing element in the table ➔ needs eviction policy
- Need to share link quality with its neighbours - see next page

The need to share link quality

- Through link estimation, each node knows the quality of the links of which it is a receiver
  - Node B knows the quality of the link A ➔ B
  - Node C knows the quality of the link A ➔ C
  - Node A knows the quality of the links B ➔ A and C ➔ A

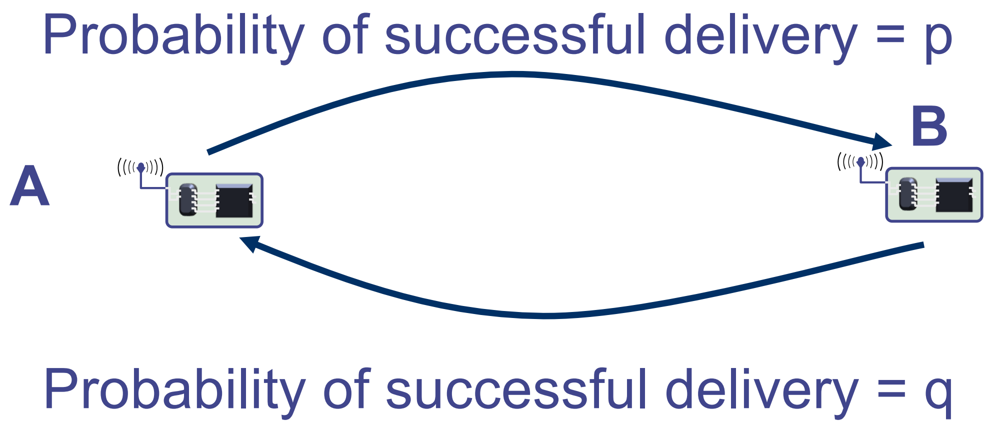


- In order for Node A to decide which neighbouring node to use, it need the quality of the links A ➔ B and A ➔ C
- This can be obtained by neighbouring nodes broadcasting its estimated link quality

Design of routing

- Based on minimum cost routing
- A distributed implementation is via Bellman-Ford
  - E.g. Routing Information Protocol (RIP). Note that RIP uses hop count but Bellman-Ford can be used for any sum-based cost metric.
- Main issue: What is a good routing metric?
- The authors evaluated a number of possible routing metric experimentally
  - Choice 1: Shortest path
  - Choice 2: Shortest path with link quality consideration
    - SP(t) uses links at with least t% delivery rate
    - E.g. SP(70) uses only links with delivery rate of 70% or greater
  - Choice 3: Minimising the number of transmissions

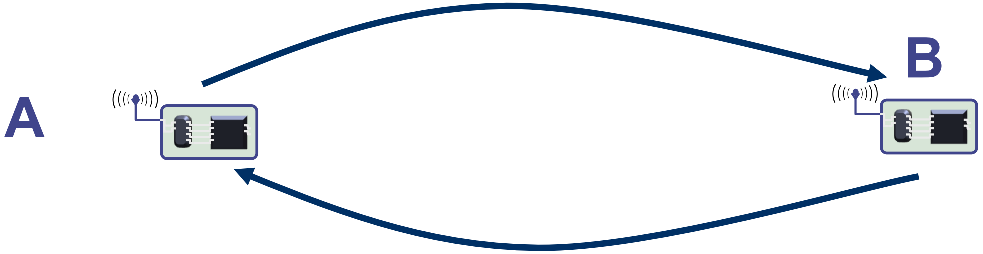
Minimum number of transmission metric (1)



- A successful unicast data exchange from Node A to Node B occurs when
  - Node A successfully sends the data packet to Node B
  - Node B successfully sends the ACK packet to Node A
- A successful unicast occurs with probability p*q
  - Assumes independence of the two probabilities

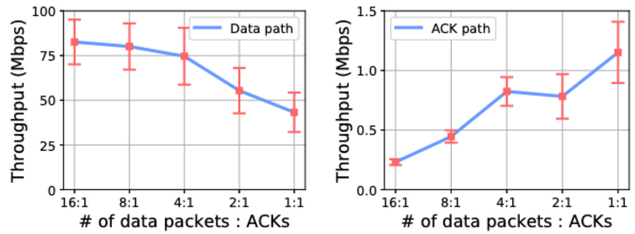
Minimum number of transmission metric (2)

Probability of successful delivery = p



Probability of successful delivery = q

- If we are allow to transmit packets as many times until we get a success, then the expected number of unicast exchanges required for Node B to successfully receive a packet from Node A is 1/(p * q)
  - Assumptions: Successive unicast packet exchanges occur with the same probability and are independent of each other

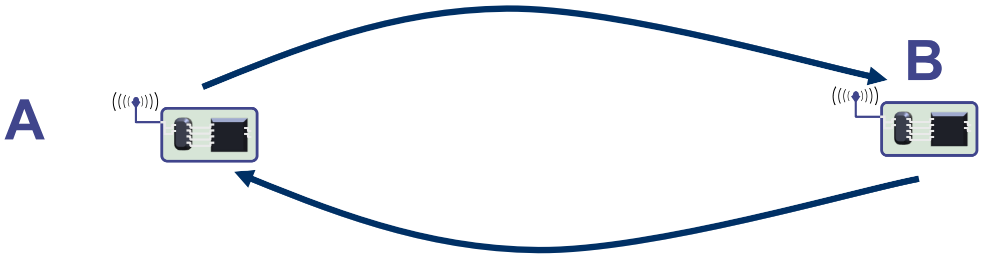


(a) Data throughput (b) ACK throughput

Figure 3: Examples for contention between data packets and ACKs over 802.11n wireless links.

“TACK: Improving Wireless Transport Performance by Taming Acknowledgments,” ACM SigCOMM 2020

Minimum number of transmission metric (3)



- Define the cost of link A ➔ B as

$$\frac{1}{\text{Link quality}_{forward}} \times \frac{1}{\text{Link quality}_{reverse}}$$

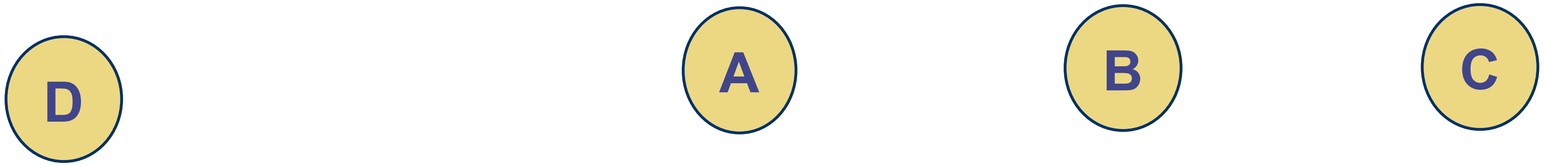
- This is known as the ETX metric in the literature where ETX stands for the expected number of transmissions

Finding the best path

- The cost of each link is given by the ETX metric
- The cost of a path is the sum of the cost of all the links in the path
- We can now use either Dijkstra or Bellman-Ford to compute the least-cost path

- Connection to energy efficiency
  - Each transmission costs energy for the transmitter as well as receiver. If we can reduce the number of transmissions, we can reduce the energy usage.
  - Does this method reduce other form of wastages, for example, overhearing?

Which box shows the expected routing behaviour?



Routing table for Node B:

Destination	Next hop	Cost to destination
D	A	10

Routing table for Node C:

Destination	Next hop	Cost to destination
D	B	8

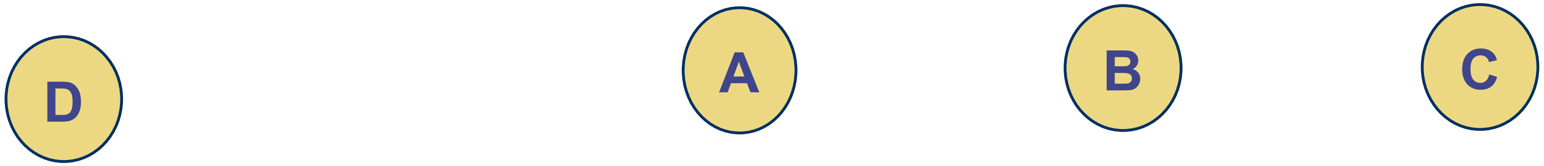
Routing table for Node B:

Destination	Next hop	Cost to destination
D	A	6

Routing table for Node C:

Destination	Next hop	Cost to destination
D	B	8

Datapath validation



Routing table for Node B:

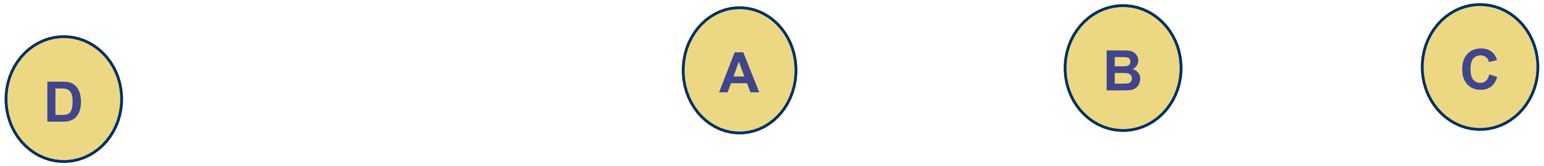
Destination	Next hop	Cost to destination
D	A	10

Routing table for Node C:

Destination	Next hop	Cost to destination
D	B	8

- Each node puts its cost to destination in the header of data packet
- When a node receives a packet to forward, it compares its cost to the destination with the cost stated in the header
- If (its cost > cost in the header), something is wrong!

How to fix the problem?



Routing table for Node B:

Destination	Next hop	Cost to destination
D	A	10

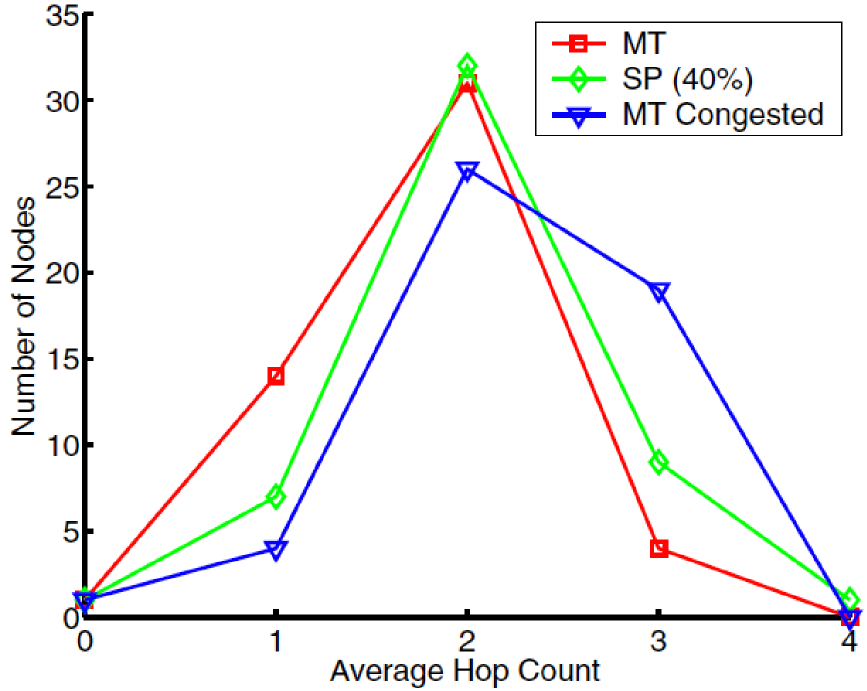
Routing table for Node C:

Destination	Next hop	Cost to destination
D	B	8

- The node that detects the problem (Node B in this example) informs Node C to update its routing table

Evaluation on a testbed (1)

- 50 nodes inside a building in a 5 x 10 grid w/ 8 foot spacing
  - 90% link quality in 8 feet
- Compare MT, SP(40), SP(70)
- SP(70) failed - can you explain why?



(a) Hop Distribution

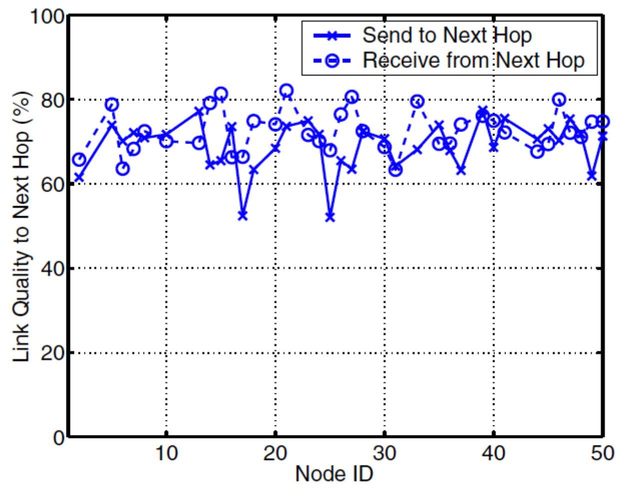


Figure 14: Non-sink node next hop link quality for MT in the foyer.

Evaluation on a testbed (2)

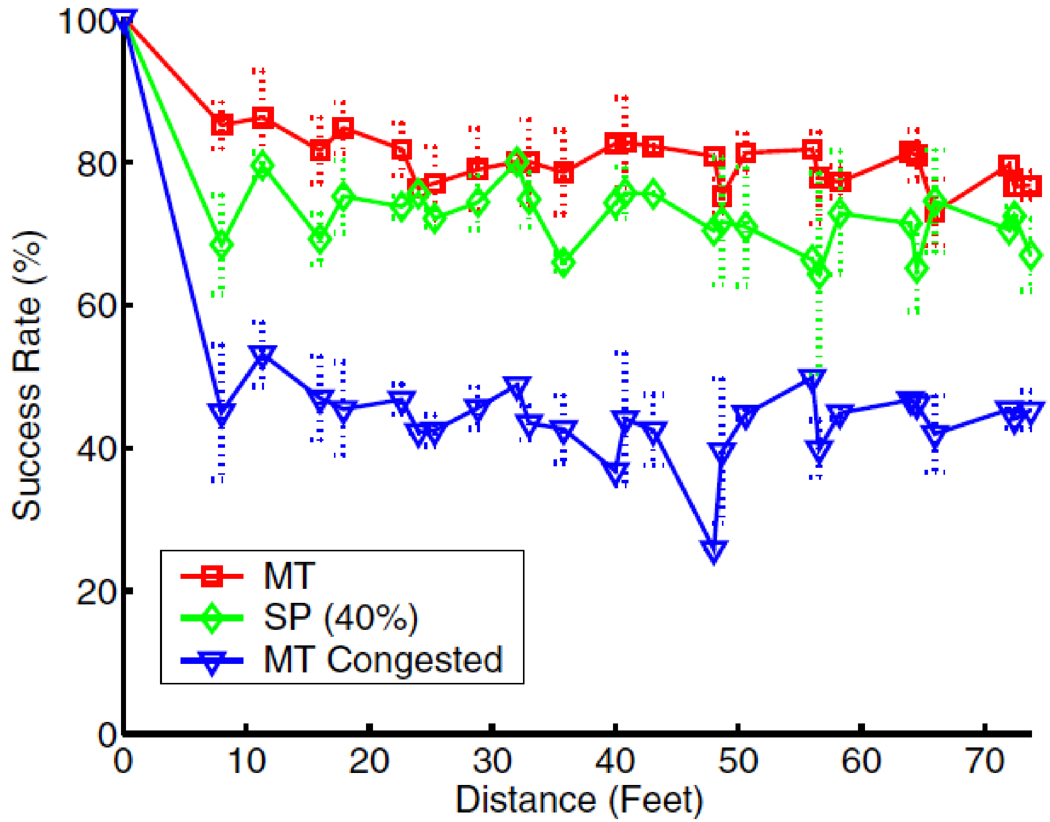
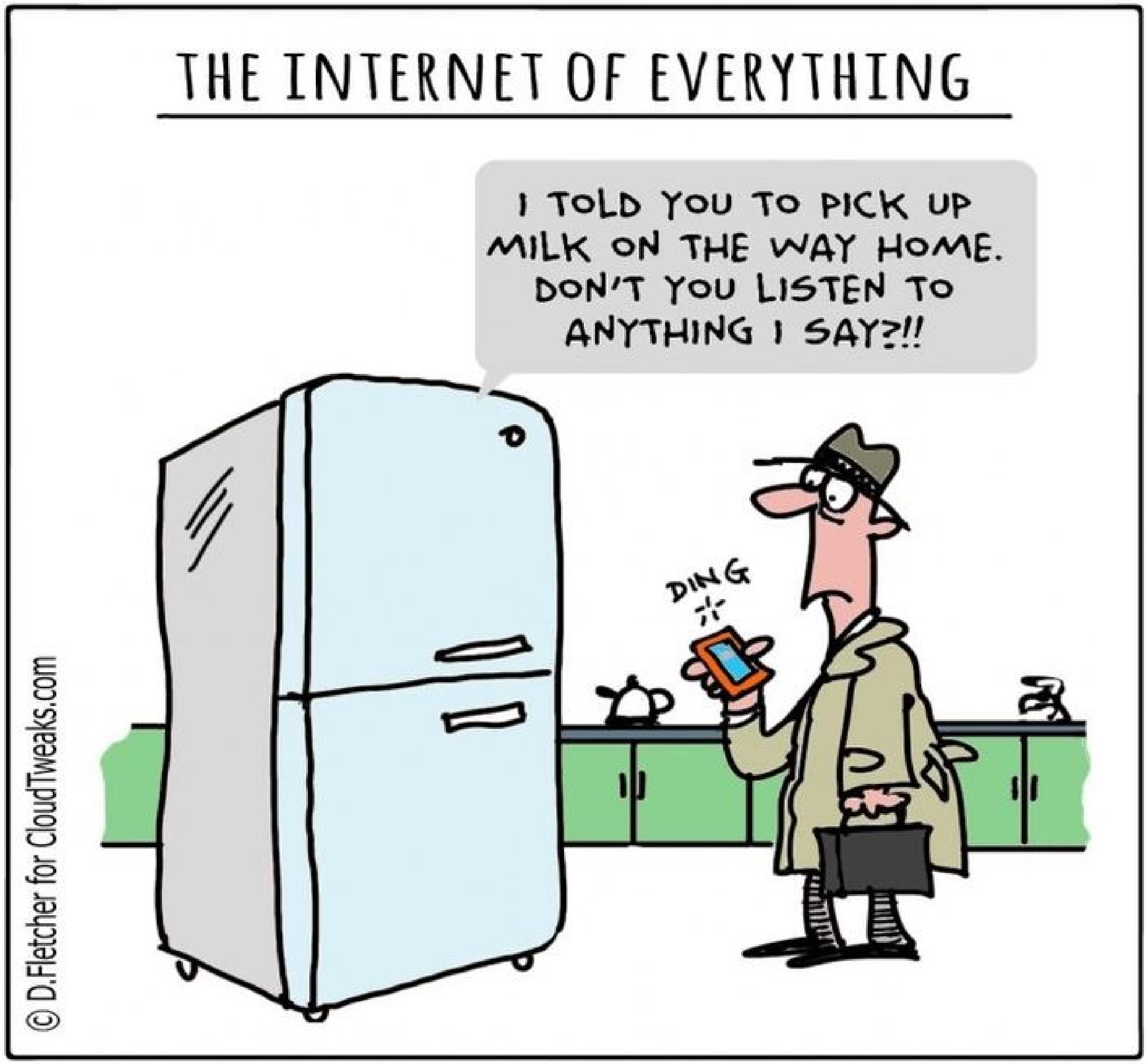
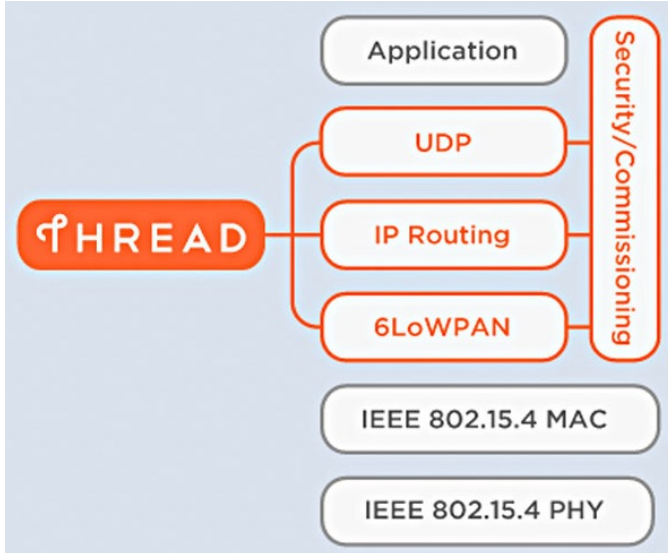


Figure 15: End-to-end success rate over distance in the foyer.


THE INTERNET OF EVERYTHING
I TOLD YOU TO PICK UP MILK ON THE WAY HOME. DON'T YOU LISTEN TO ANYTHING I SAY?!!
DING
© D.Fletcher for CloudTweaks.com

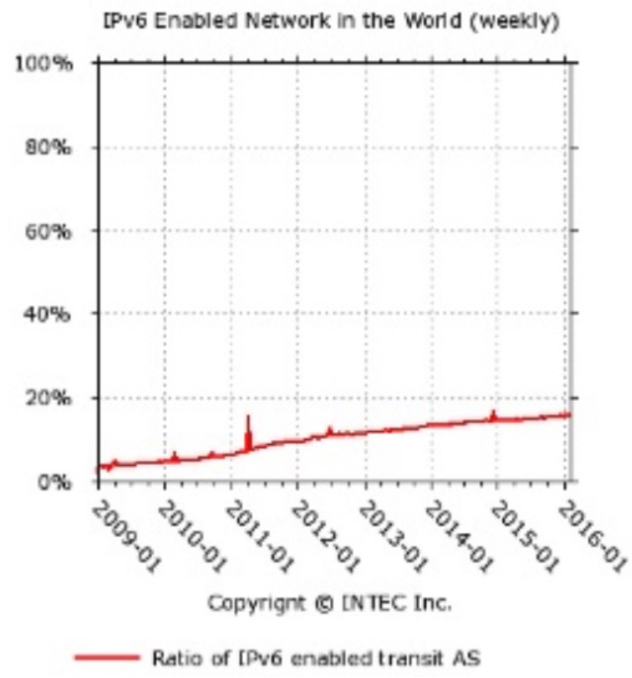
6LoWPAN

- Low-power RF + IPv6 = The Wireless Embedded Internet
- 6LoWPAN makes this possible
- The benefits of 6LoWPAN include:
  - Open, long-lived, reliable standards
  - Easy learning-curve
  - Transparent Internet integration
  - Network maintainability
  - Global scalability
  - End-to-end data flows



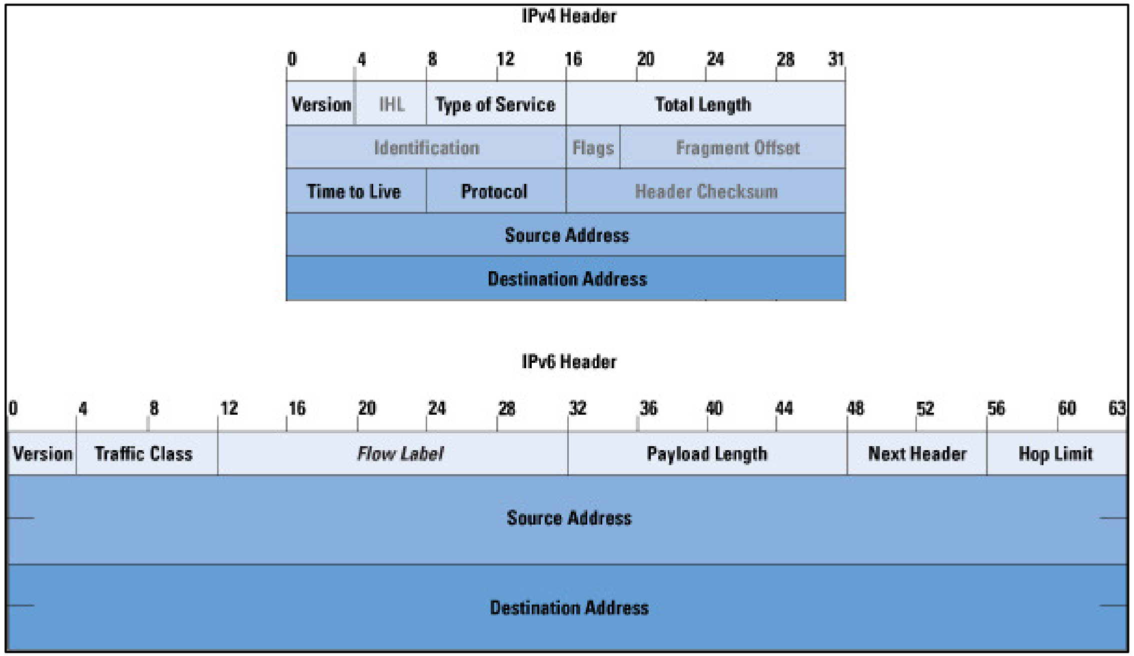
Internet Protocol v6

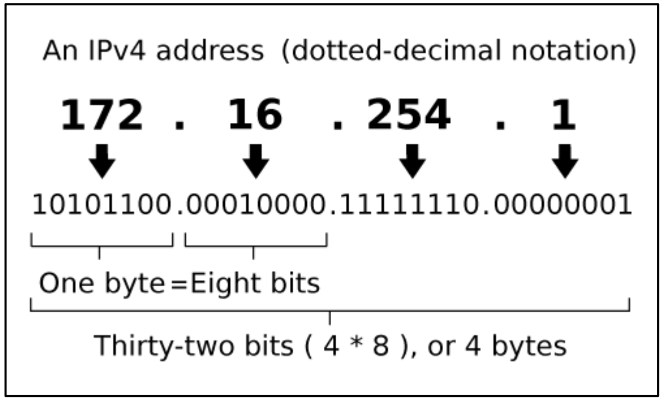
- IPv6 (RFC 2460) = the next generation Internet Protocol
  - Complete redesign of IP **addressing**
  - Hierarchical 128-bit address with decoupled host identifier
  - Stateless auto-configuration
  - Simple routing and address management
- Majority of traffic not yet IPv6 but…
  - Most PC operating systems already have IPv6
  - Governments are starting to require IPv6
  - Most routers already have IPv6 support
  - So the IPv6 transition is coming
    - About 20% penetration as of 2017

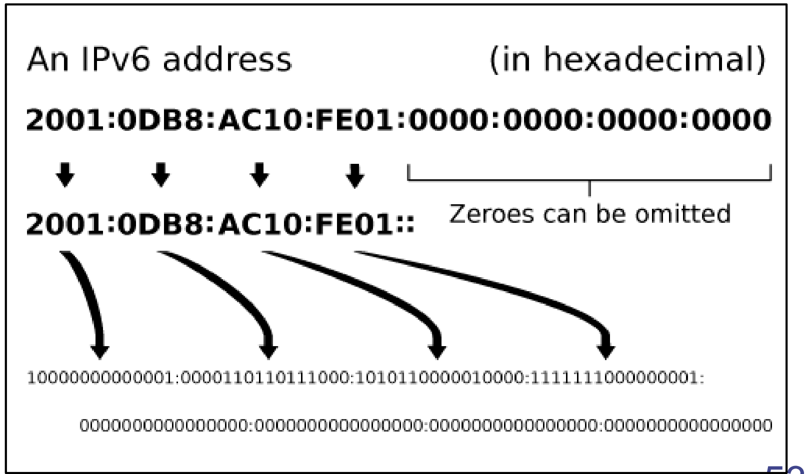


IPv4 vs. IPv6

- IPv6 looks big, will it work for wireless devices with packet length restrictions?

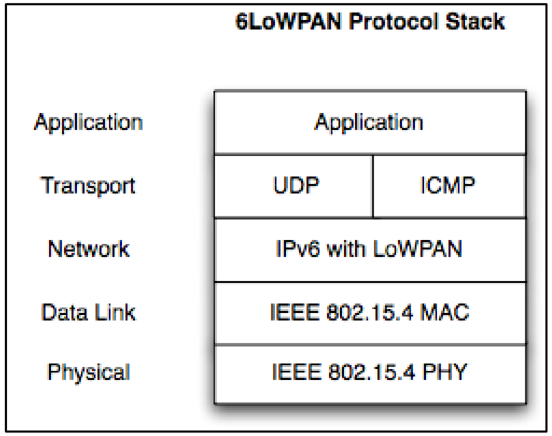






6LoWPAN Advantages

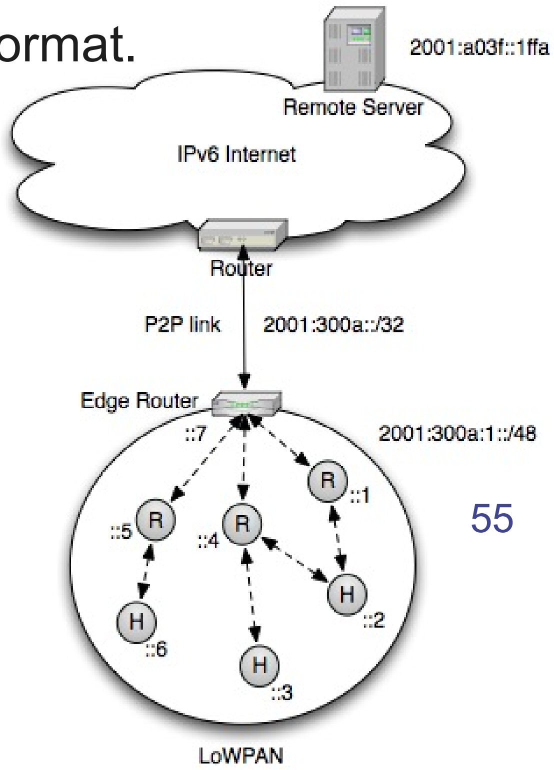
- Compression of packets
  - Source (16 bytes) and destination (16 bytes) is a lot to transfer over the air.
  - May reconstruct from lower level protocol layers.
    - **IEEE 802.15.4**



- Expandable headers:
  - ICMPv6 (Internet Control Message Protocol).
    - **Here we may have RPL Control messages**
    - Pings.
  - Hop-by-Hop Option:
    - May include RPL Options in application messages. Extra diagnosis info.
  - UDP (Source Port, Destination Port, Length, Checksum). Then comes your application data.
  - Fragmentation: larger packets may be reconstructed multiple smaller packets.

6LoWPAN Addressing

- IPv6 addresses are compressed in 6LoWPAN
- A LoWPAN works on the principle of
  - Flat address spaces (wireless network is one IPv6 subnet)
  - With unique MAC addresses (e.g. 64-bit or 16 bit)
- 6LoWPAN compresses IPv6 addresses by
  - Eliding the IPv6 prefix
    - Global prefix known by all nodes in the network
    - Link-local prefix indicated by header compression format. FE80::/10
  - Compressing the Interface ID
    - Elided for link-local communication
    - Compressed for multi-hop dst/src addresses
  - Compressing with a well-known “context”
  - Multicast addresses are compressed

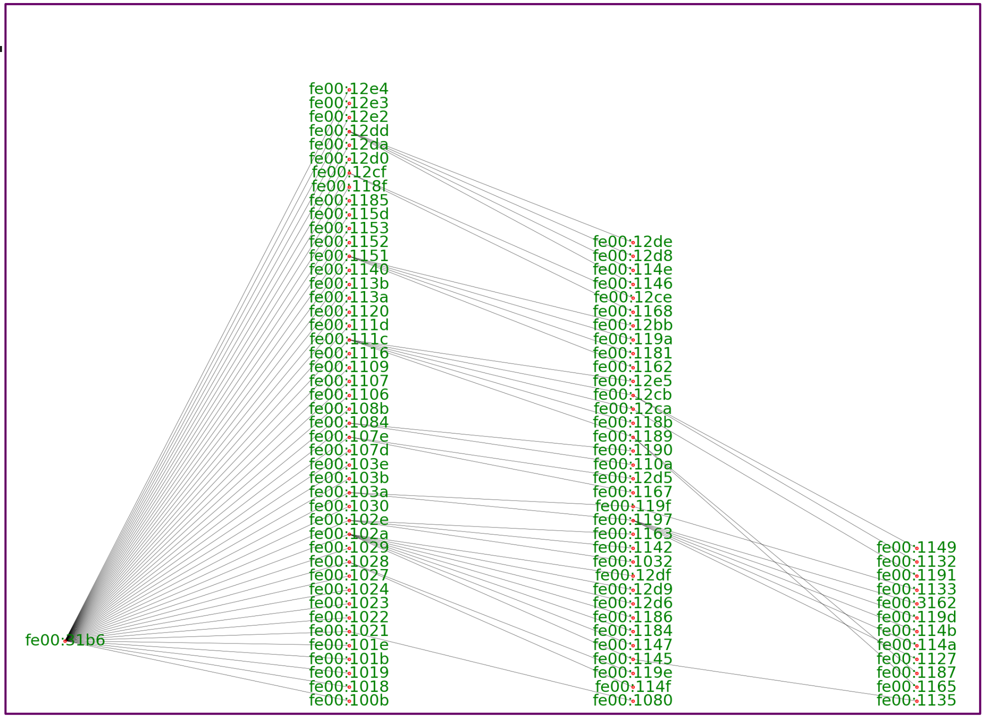


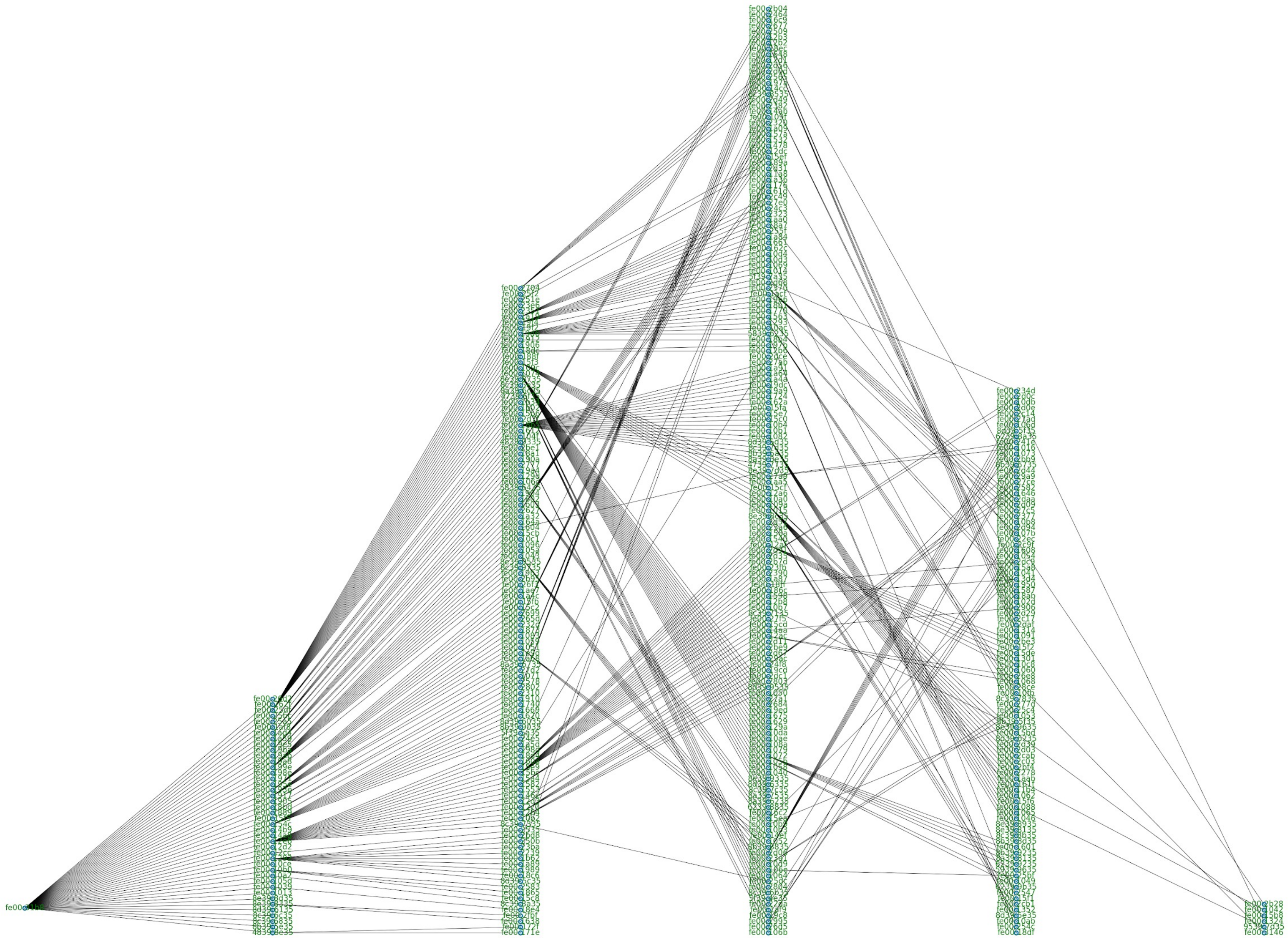
RPL --- Routing Protocol for Low-Power and Lossy Networks

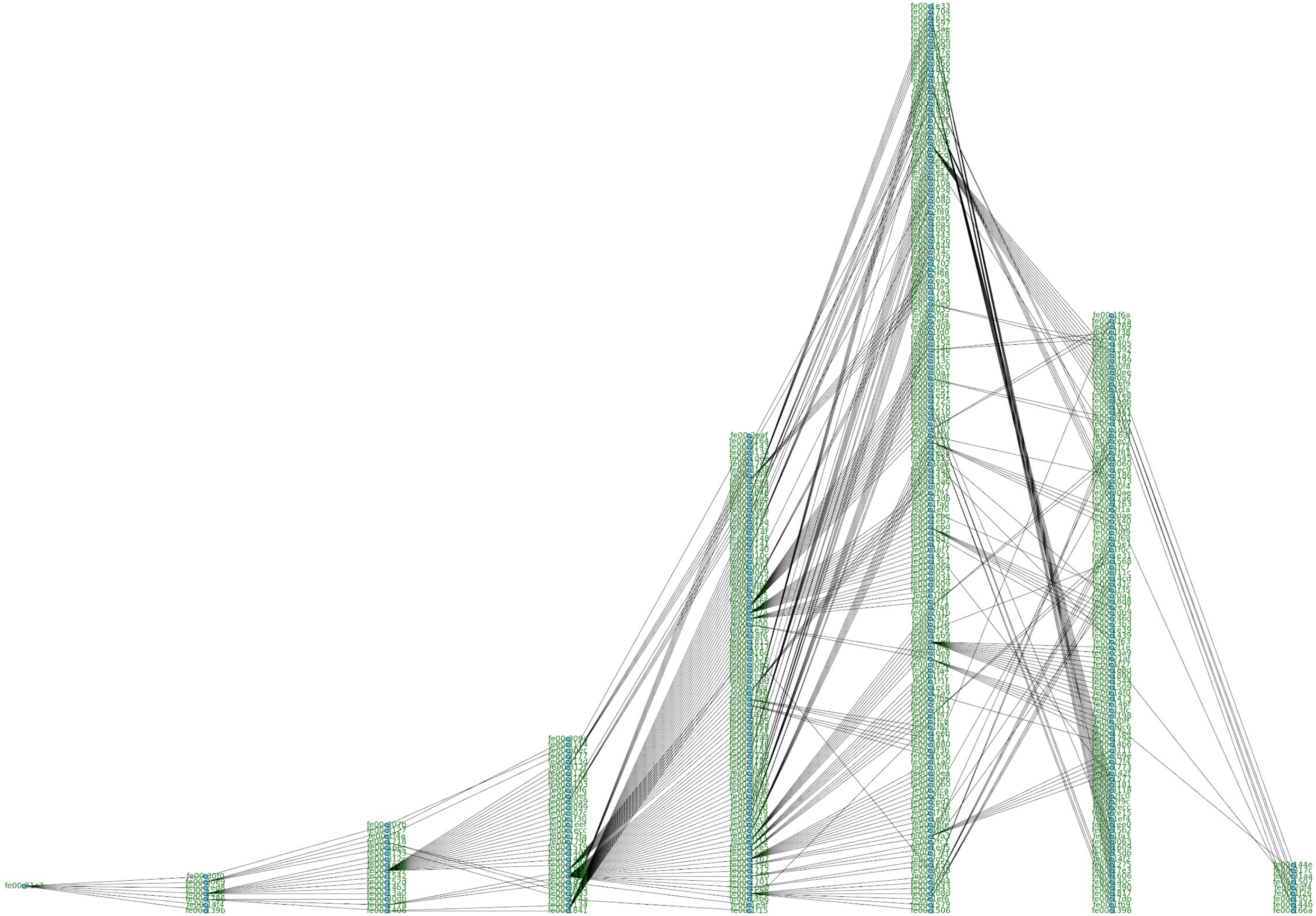
- Dealing with:
  - Low power and Lossy Networks (LLNs) consisting of constrained nodes.
  - Lossy and unstable links, typically supporting low data rates, and relatively low packet delivery rates
  - Potentially comprising up to thousands of nodes.
- Application specific requirements:
  - Home automation
  - Commercial building automation
  - Industrial automation
  - Urban environments
- Protocol called RPL, pronounced Ripple:
  - RFC6550 - a proactive distance vector approach
  - Routing Over Low power and Lossy networks (ROLL)

ROLL RPL

- Routing based upon one or more DODAGs:
  - Destination Oriented Directed Acyclic Graph
  - Means there are no loops, like a tree. Ending up or down.
  - Direction is up or down (application packets), with some exceptions.
- Each node selects a parent:
  - Least overall cost to get to Border router
  - According to Objective Function.
  - May deal with multiple DAGs.

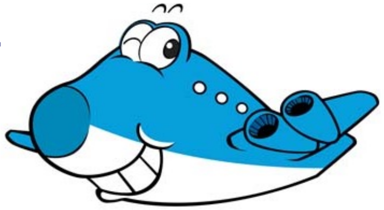


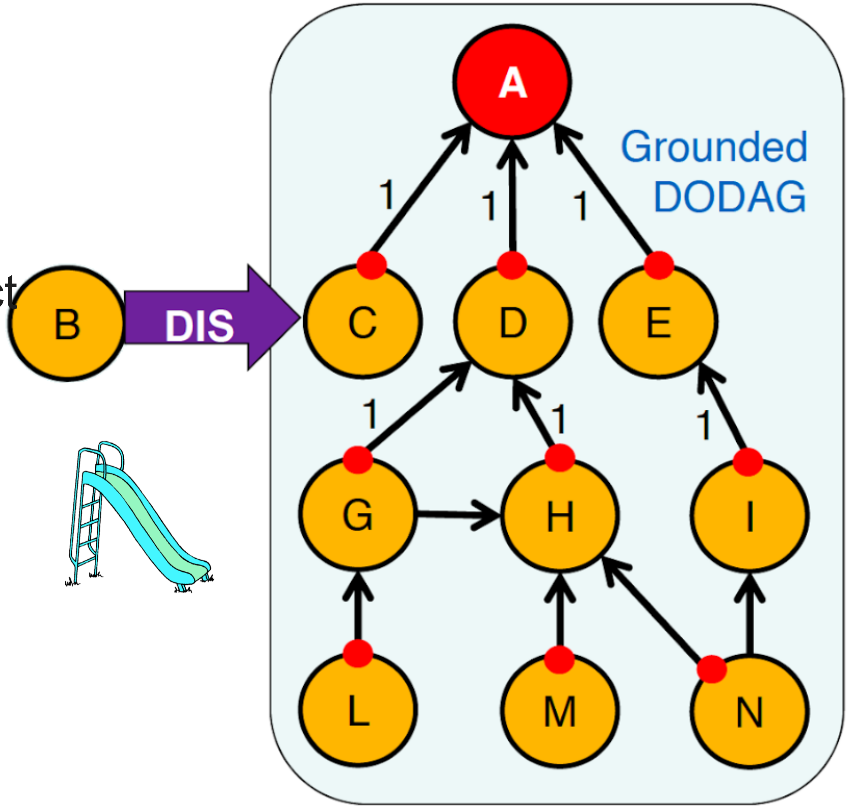


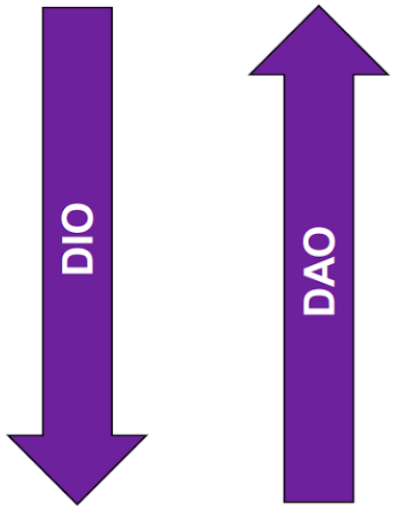


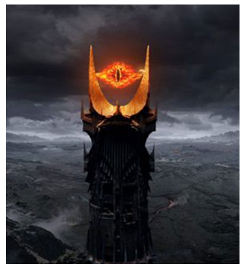
RPL control messages

- DIS
  - DODAG Information Solicitation
  - Broadcast
- DAO
  - Destination Advertisement Object
  - Unicast
- DIO
  - DODAG Information Object
  - Unicast (probing)
  - Broadcast (timer)



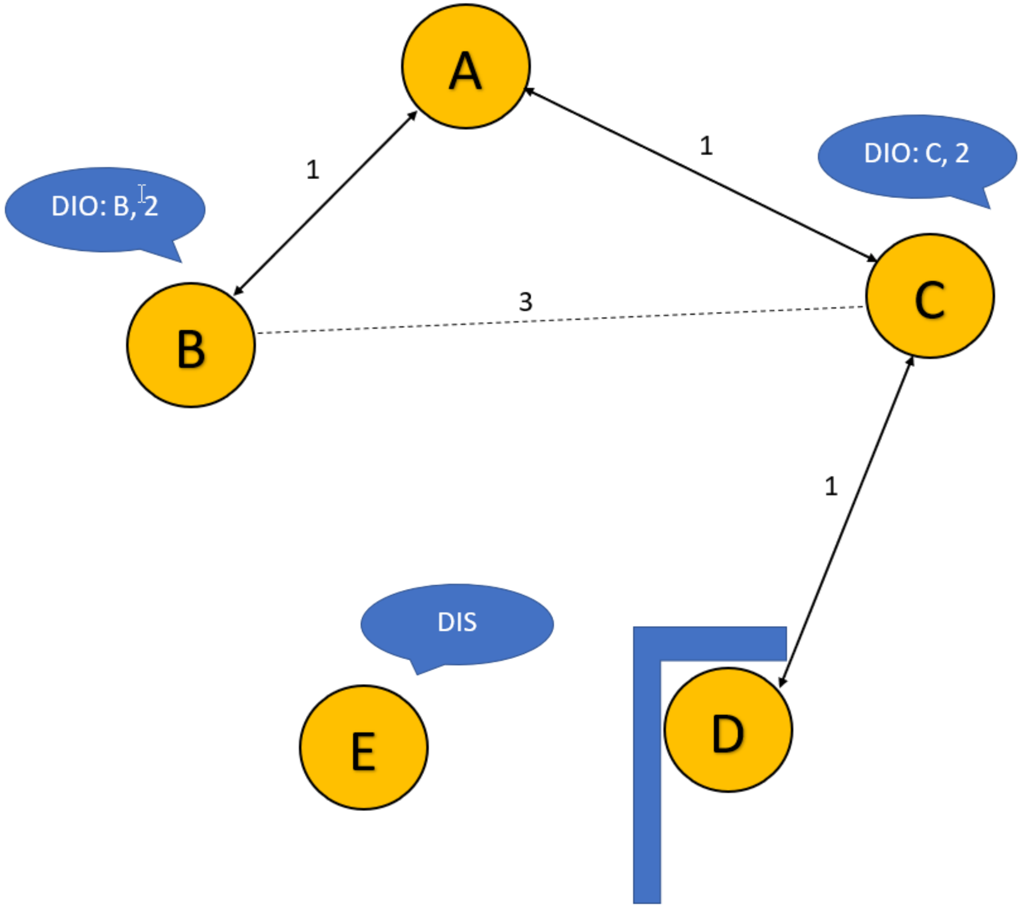






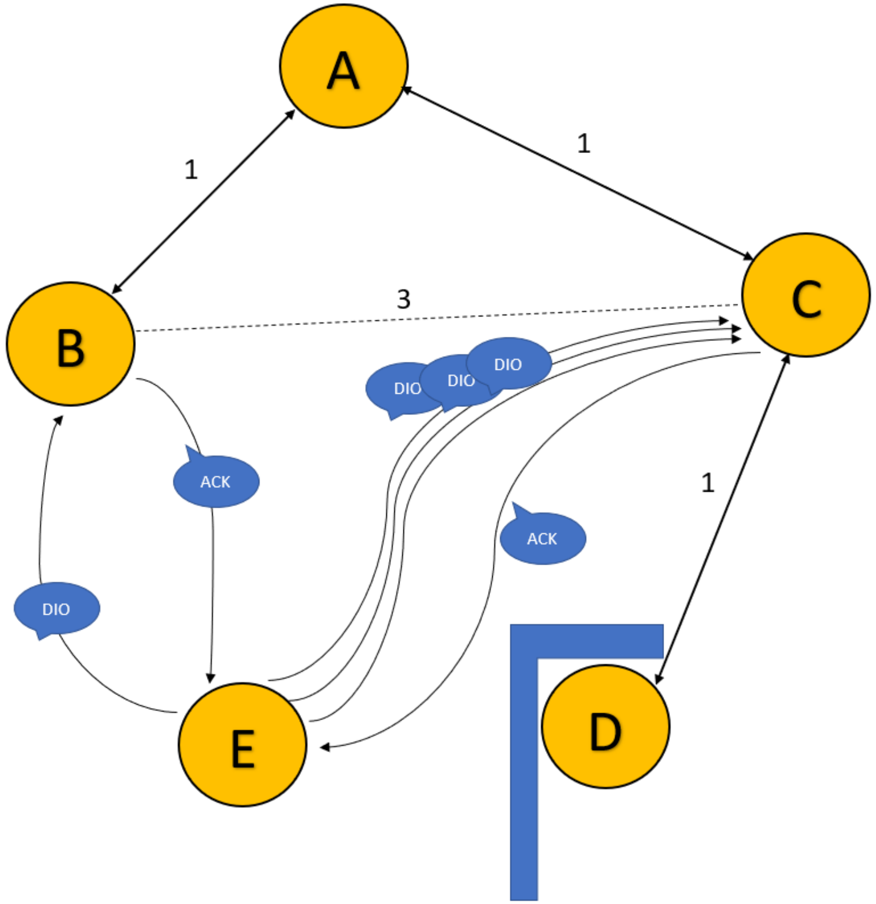
Joining network

- Broadcast commands!
- New node send DIS to cause other nodes to reset their DIO Timers.
  - Network may initially be quiet.
  - Aims to hear a DIO soon.
- Registered nodes will periodically send multicast DIOs based off a Timer:
  - Interval increase as network stabalises.
  - Why?



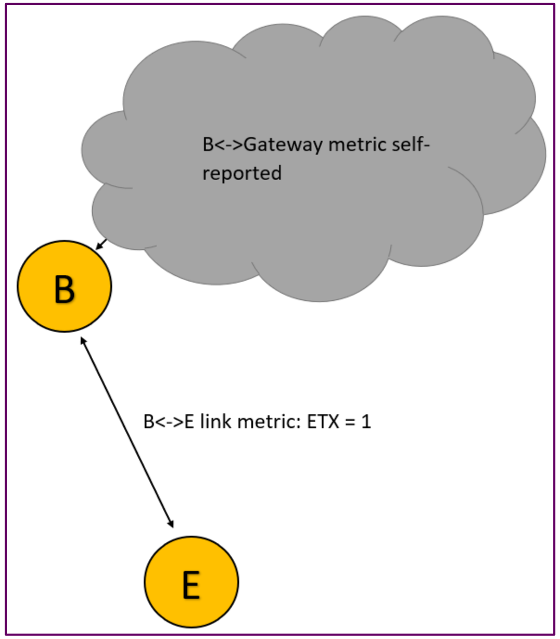
Probing your neighbours

- Unicast commands!
- Nodes probe neighbours for:
  - Urgent probing to find initial parent
  - Network maintenance
- Unicast-DIO probe expects a reply:
  - Minimum **Rank** with Objective Function.
  - Lower levels have retry mechanism.
  - Expected Number of Transmissions (ETX) used for DODAG optimisation as input to the Objective Function to minimise rank.
- May optimise for other metrics, may include:
  - Battery, spatiotemporal correlation



Parent Selection (upwards route)

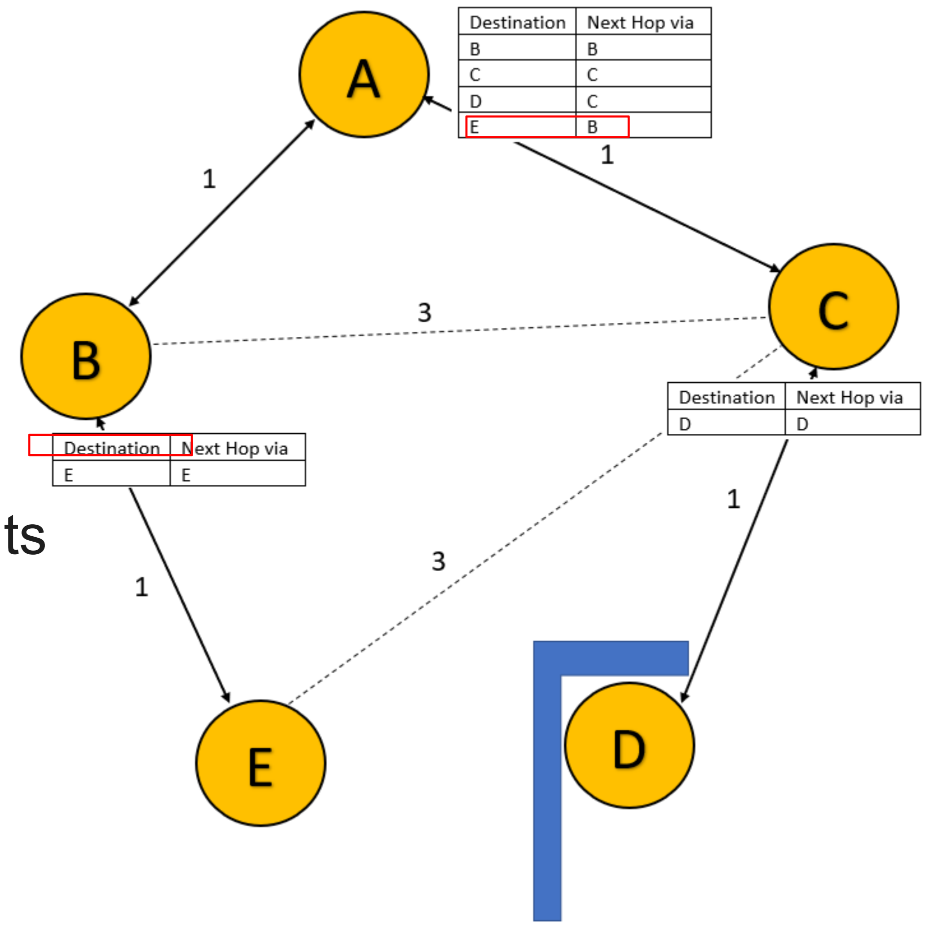
- When receiving DIOs:
  - Node will be able to create a neighbour table.
  - The cost of a link: neighbouring node's cost to reach the gateway + the cost to reach the neighbouring node.
- The total cost is improved over time.
  - First take default estimated (RSSI) value, then improved over time.
  - “Urgent” probing. Quick probing outside of regular probing interval.



Neighbour E to:	ETX of Neighbour to Gateway	ETX of link to Neighbour	Total
B	**2**	**1**	**3**
C	2	3	5

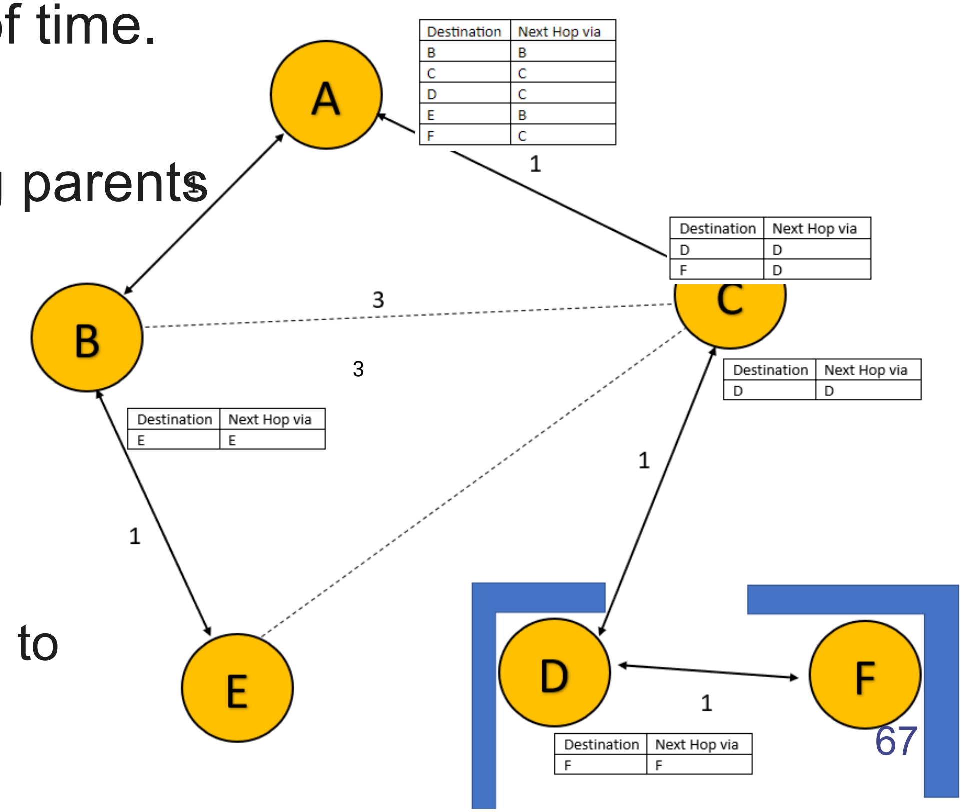
Route Registration (downward route)

- When preferred parent is chosen:
  - The node will set up a DAO (going upwards) back its parent.
  - The parent/grandparent node will forward the DAO, until reaching the Gateway.
- Storing Mode:
  - Each parent has a table to route to its grandchildren via immediate hop.
  - DAO received leads to new routing entry.
- Non-storing mode:
  - Gateway is responsible for routing. Route is in the packet.
  - Each parent forwarding DAOs add additional information in headers.



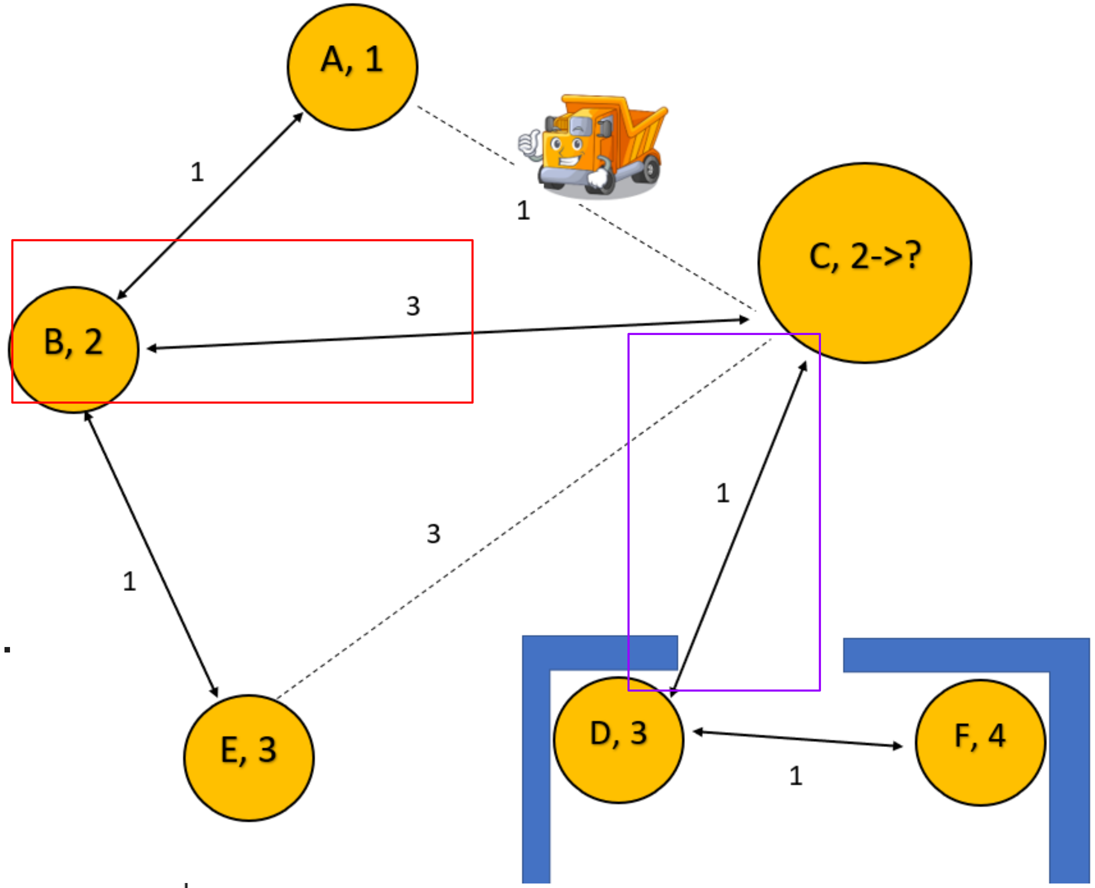
Route maintenance

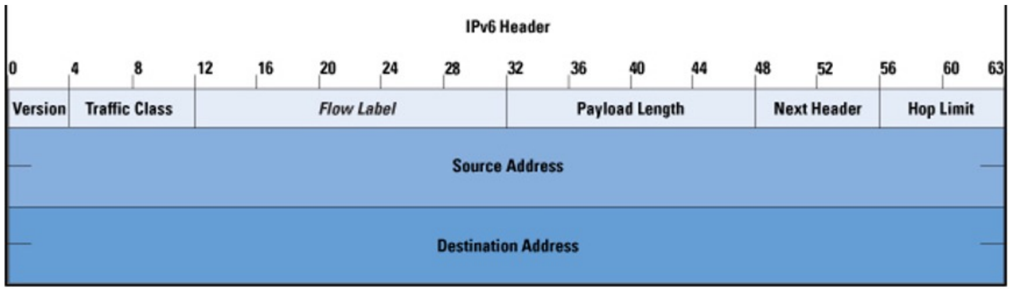
- Nodes regularly:
  - Probe its neighbours to obtain each link's ETX.
  - Get updates from neighbours.
  - Convergence to true ETX value of time.
- Parent switching:
  - Speed and likelihood of switching parents is done via a Object Function.
  - Reduces **Churning**
  - No-Path DAO to previous parent.
  - DAO to new parent.
  - Node then resets its DIO timer.
    - DIO from parent causes children to schedule DAOs.



Loop detection

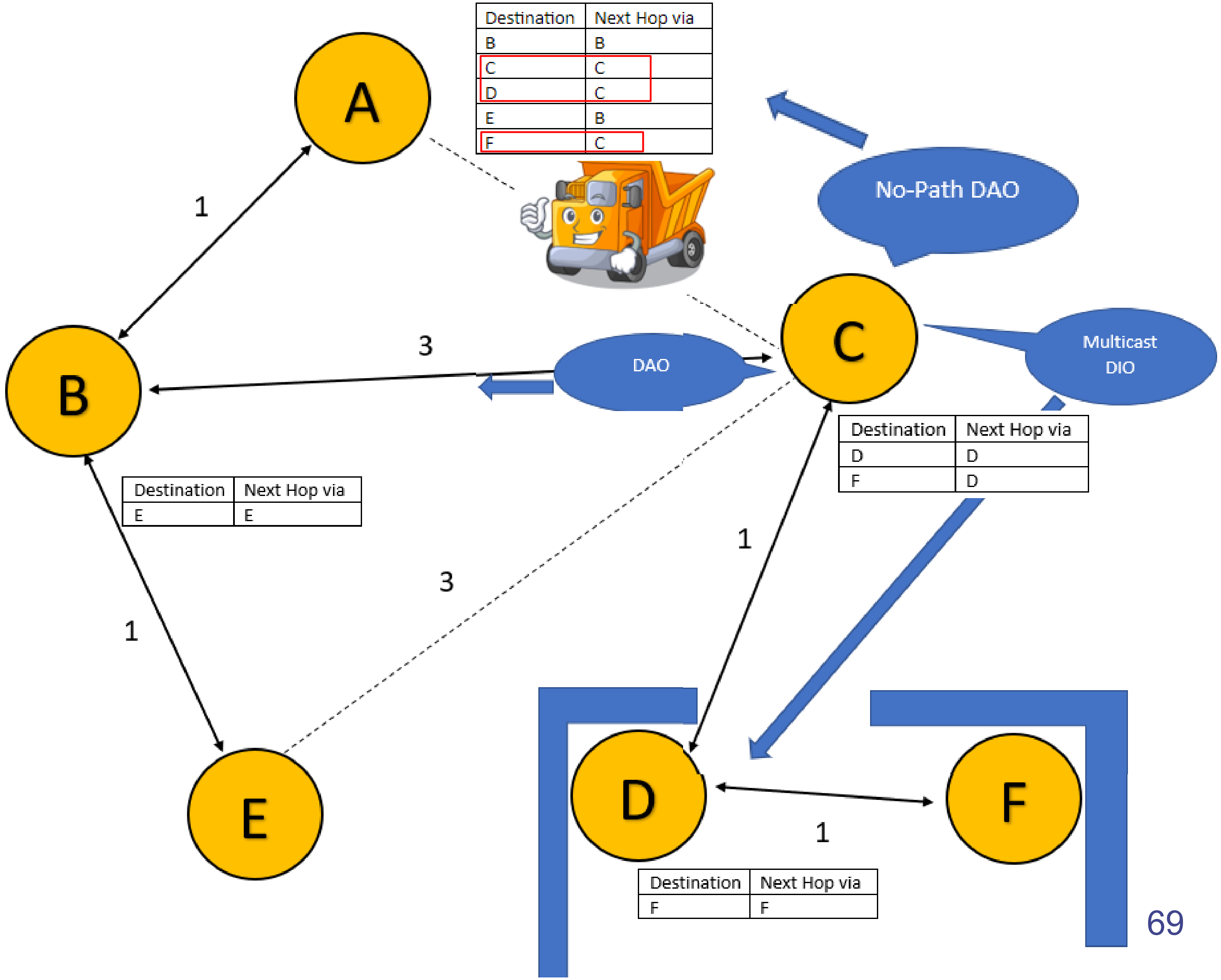
- A <-> C link has been broken. C needs new parent:
  - Pick B: 2 + 3 = 5
  - Pick D: 3 + 1 = 4
  - Going via D has lower cost!?
- Won't this cause a loop?
  - C receives DAO from D; Split horizon
  - B will end up as better choice.





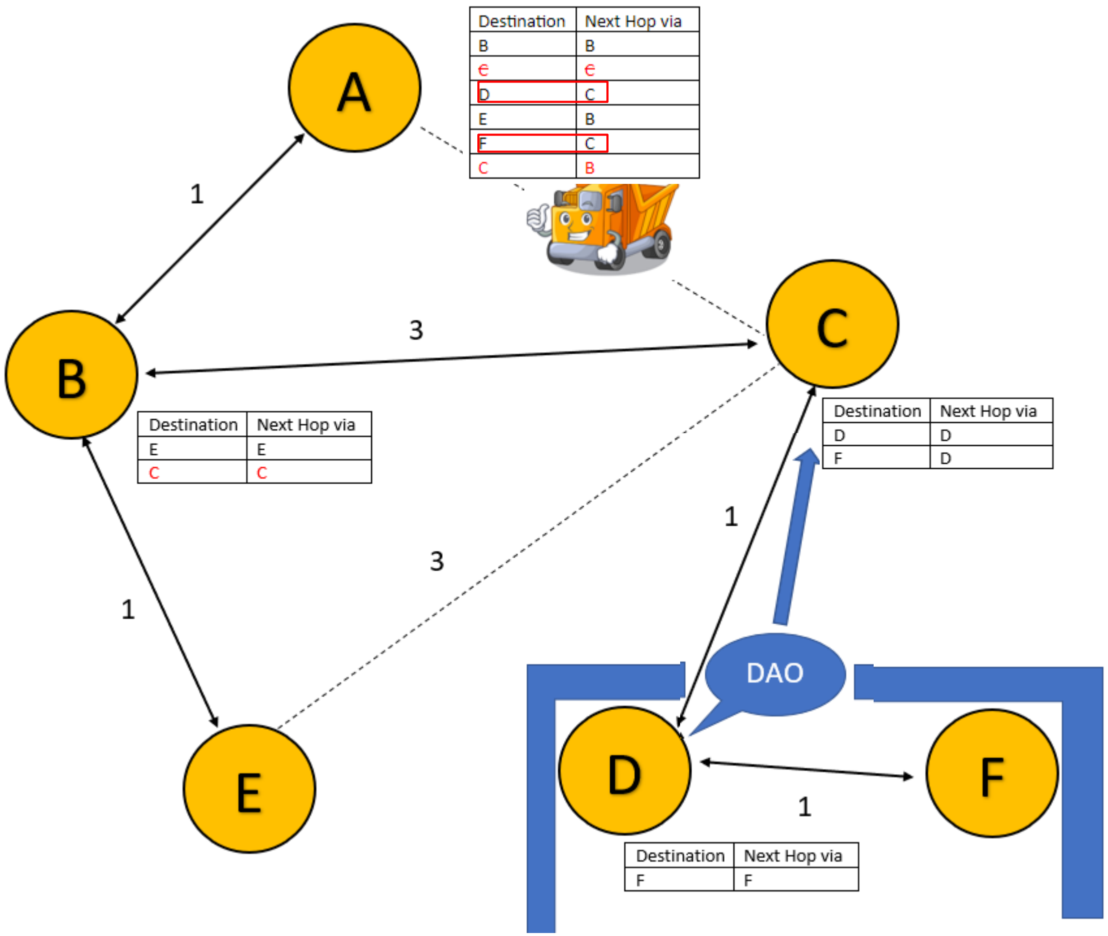
Route maintenance (2)

- C struggles to send a No-Path to A.
- C sends a DAO to B.
- C resets its timer.
    - Causes children to send DAO.



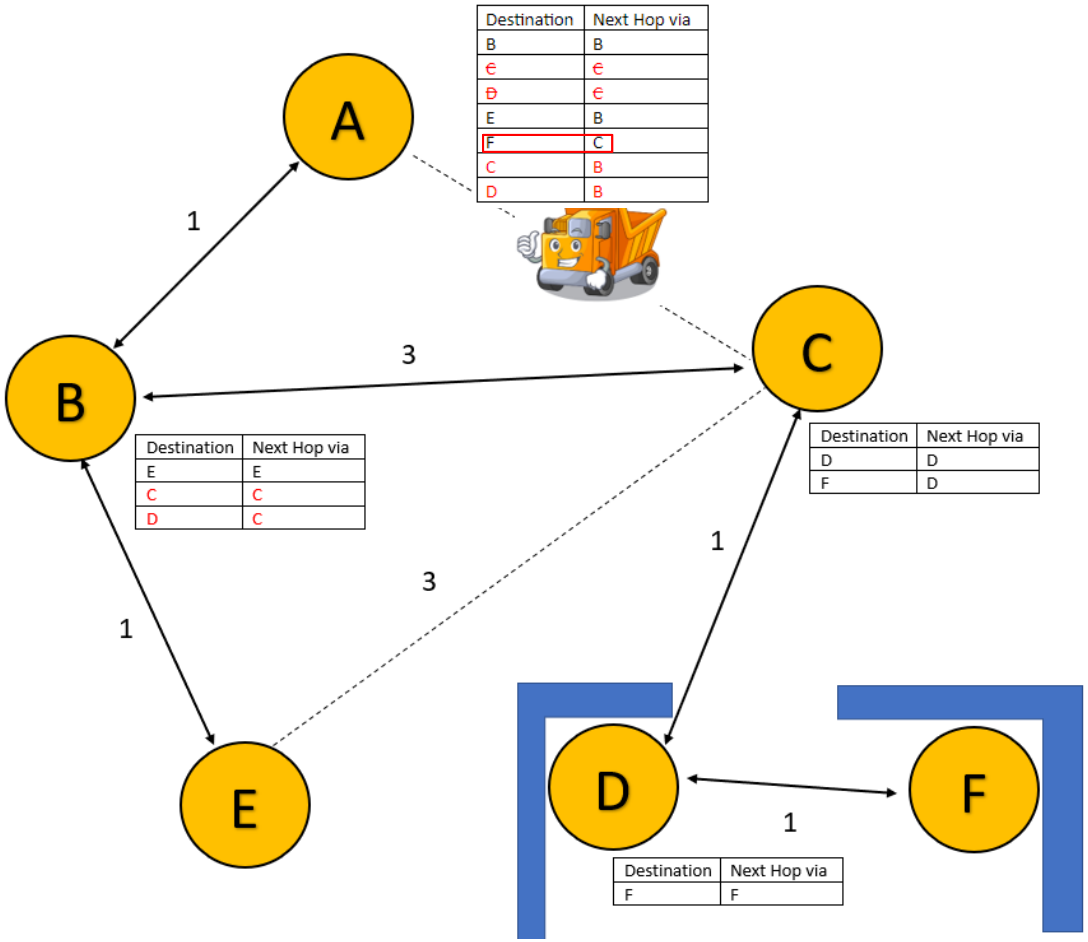
Route maintenance (3)

- Route is fixed for C.
- D and F routes are still broken.
- D will send a DAO as C's reset timer has sent a DIO.
  - C will then forward DAO onwards, until reaching A.



Route maintenance (4)

- Route is fixed for D.
- Route will be broken for F until it's DAO timer gets triggered.
  - When D has its DIO timer going off.
  - In this example, D's DAO timer has never been reset.



Challenges

- Large network with large interference range
  - Parent swap is expensive
  - Means temporary broken link to (great+)grandchildren
  - Large routing table
  - Large neighbourhood table
- **Balance** between RPL messages and Application messages
  - Timers could improve route, or add to the problem
  - Better ways to probe: **freshness** (probabilistic instead of round robin)
  - Testing impacts ETX
- Dealing with multiple DAGs

Reading

- IEEE 802.15.4 standard
- Collection tree protocol:
  - Woo, Tong, and Culler. "Taming the underlying challenges of reliable multihop routing in sensor networks." (available from course web site)
  - Gnawali et. al. "Collection tree protocol." " (available from course web site)
- 6LoWPAN and ROLL
  - IETF RFC 6550. "RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks"
  - IETF RFC 6282. "Compression Format for IPv6 Datagrams over IEEE 802.15.4-Based Networks"