Lecture 07
Thread

CS397/497 – Wireless Protocols for IoT

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With some advice from Neal Jackson (UC Berkeley)

Materials in collaboration with
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Administrivia

- Hw: BLE Packets due today
  - Do it. It’s good for you. Much like eating spinach.

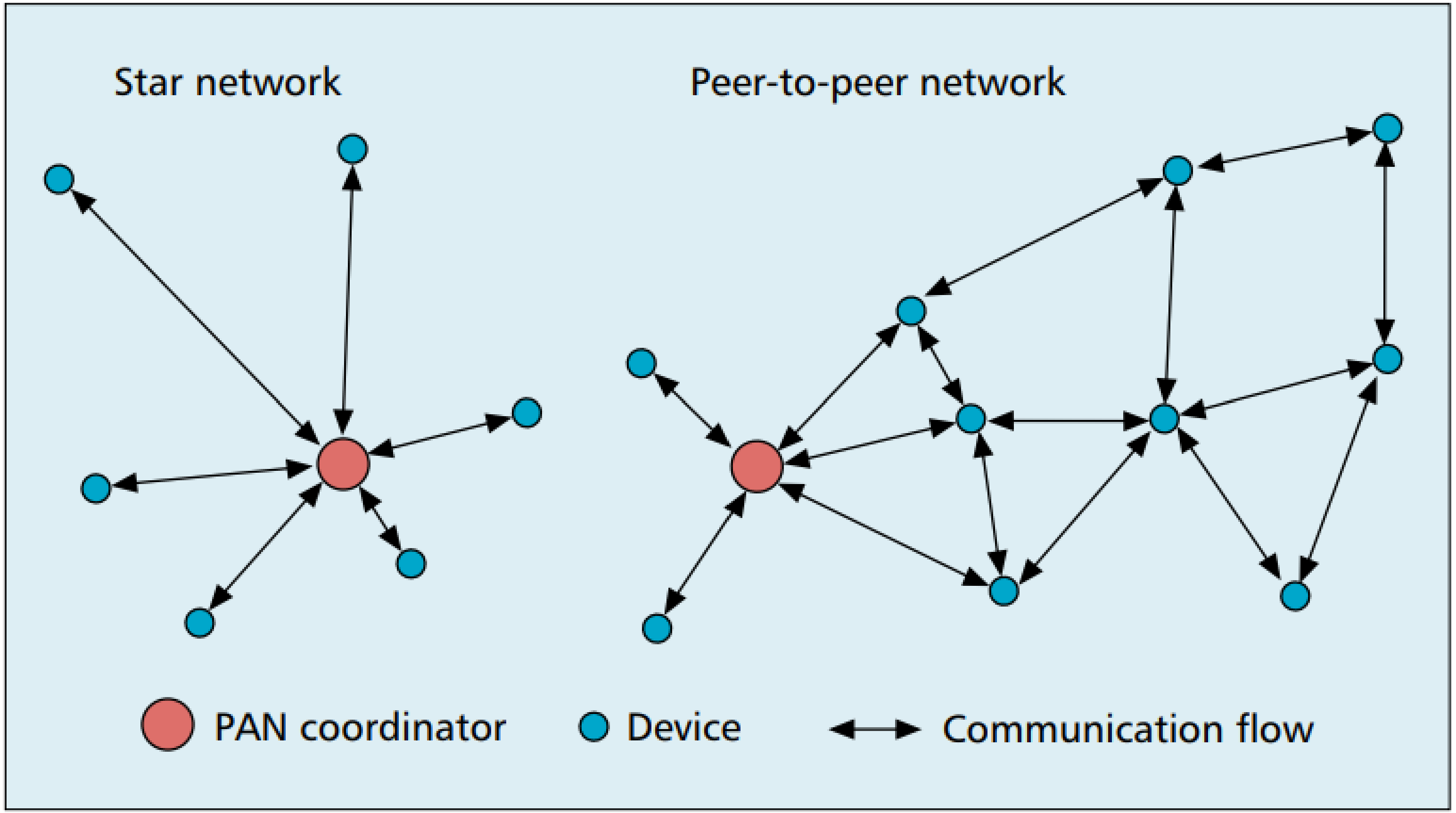
- Lab: BLE due on Tuesday
  - If you haven’t started, do so ASAP
  - Some people had various hardware/software issues getting started
    - Once you’ve gotten to “blink an LED”, everything should be good from there

Today's Goals

- Explore 802.15.4 packet structure
- Describe goals and capabilities of Thread networks
- Understand addressing in Thread networks
- Describe runtime behaviors like network joining

802.15.4 network topologies

- Only specifies PHY and MAC, but has use cases in mind



Modes of operation

- Beacon-enabled PAN
  - Slotted CSMA/CA
  - Structured communication patterns
  - Optionally with some TDMA scheduled slots

- Non-beacon-enabled PAN
  - Unslotted CSMA/CA
  - No particular structure for communication
    - Could be defined by other specifications, like Thread or Zigbee

Beacon-enabled superframe structure

- Beacons occur periodically [15 ms – 245 seconds]
  - Devices must listen to each beacon
- Contention Access Period
  - Slotted CSMA/CA synchronized by beacon start time
- Inactive Period
  - No communication occurring. Assumes sleepy devices

Non-beacon-enabled PAN

- Same idea, just no beacons
  - Which removes synchronization benefit (and slotted CSMA/CA)
  - Also removes beacon listening cost
    - Devices only need to check for activity before transmitting
  - Still need an algorithm to determine when it should receive data
    - All the time is a huge energy drain
    - Algorithms can get complicated here
    - **Could BLE mechanism of listen-after-send apply?**
      - Only if sending to a high-power device, not among equals

802.15.4 specification versions

- 2011
  - Four PHY options (UWB)
  - MAC capability to support ranging (distance measurements)

- 2015
  - Six PHY options (RFID, Smart Utility, TV White Space)
  - Time Slotted Channel Hopping (TSCH) access control (TDMA+FDMA)

- 2020
  - Several new PHY options (China medical band, alternate modulations)

Major 802.15.4 uses

- Zigbee & Thread

- Both build upon the 15.4 PHY and Link primitives
  - Using most but discarding some

- Both consider higher-level application considerations
  - Building a network
  - Communicating between devices
  - Application logic

Outline

- **Thread Overview**
- Thread Addressing
- Runtime Behavior
- Using IP

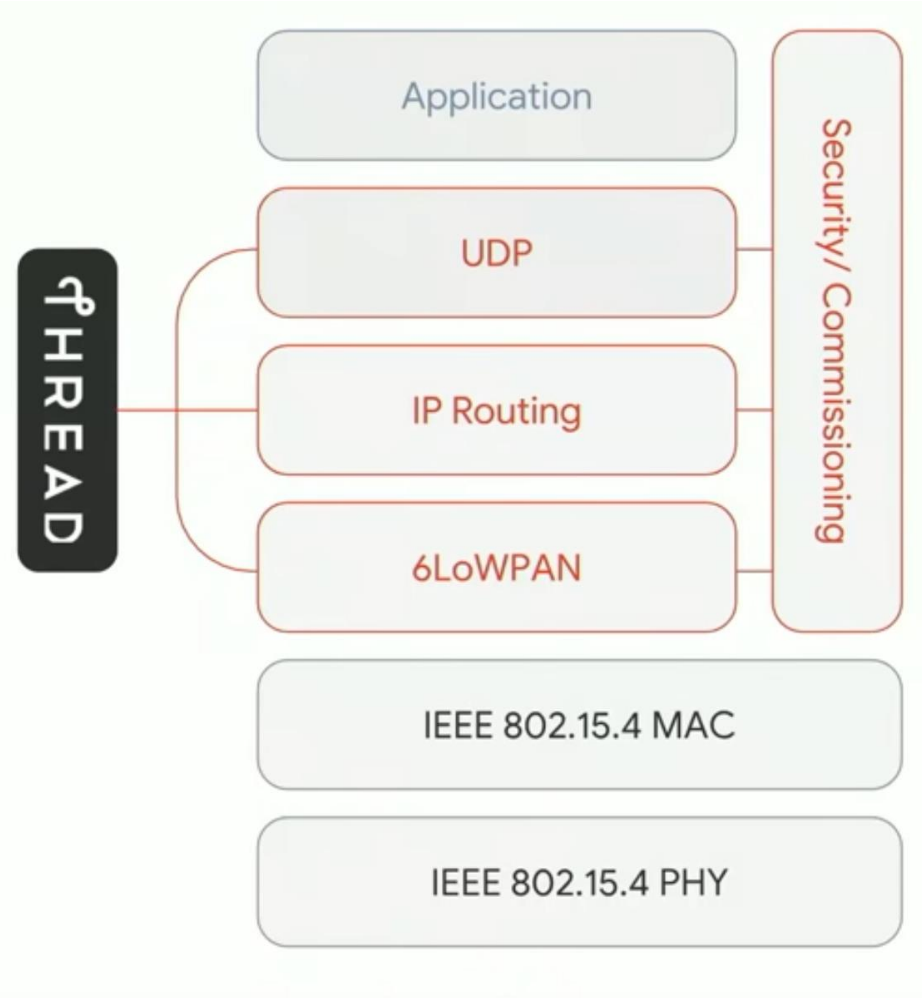
What's the need for Thread?

- Born from Google's Nest team
- Requirements:
  - IP-based: interoperate with rest of the Internet
  - Scalable: hundreds of devices in a network
  - Low power: years of operation on batteries
  - Secure: authenticated and encrypted communication
  - Reliability – mesh networking without single point of failure
- 2014: Thread Group alliance formed
  - Goal: develop, maintain and drive adoption of Thread as an industry networking standard for IoT

Source: openthread.io, threadgroup.org

Thread overview

- Build a networking layer on top of 15.4
  - Reuses most of PHY and MAC
  - Adds IP communication
  - Handles addressing and mesh maintenance
- Industry-focused, but based in academic research



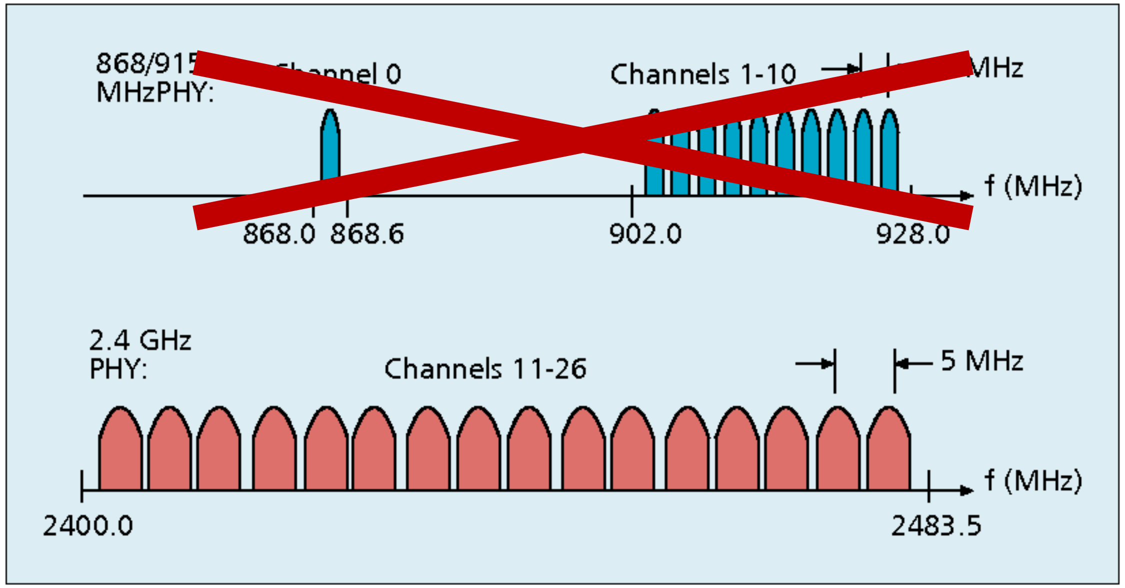
References on Thread

- Request for specification: https://www.threadgroup.org/ThreadSpec
  - Frustratingly locked down 😡
- Overview on capabilities: https://openthread.io/guides/thread-primer
  - Excellent overview
  - Lifting heavily for these slides
- Good overview on Thread Networking:
  - https://www.threadgroup.org/support#Whitepapers
  - See the “Thread Network Fundamentals” whitepaper

Changes to Physical Layer

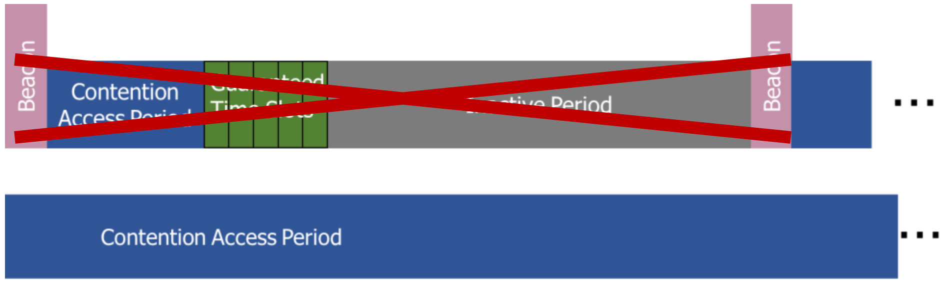
- Remove all non-2.4 GHz PHY options

- Otherwise the same
  - O-QPSK
  - 16 channels, 5 MHz spacing
  - Typical TX power 0 dBm
  - Typical RX sensitivity -100 dBm



Changes to Link Layer and MAC

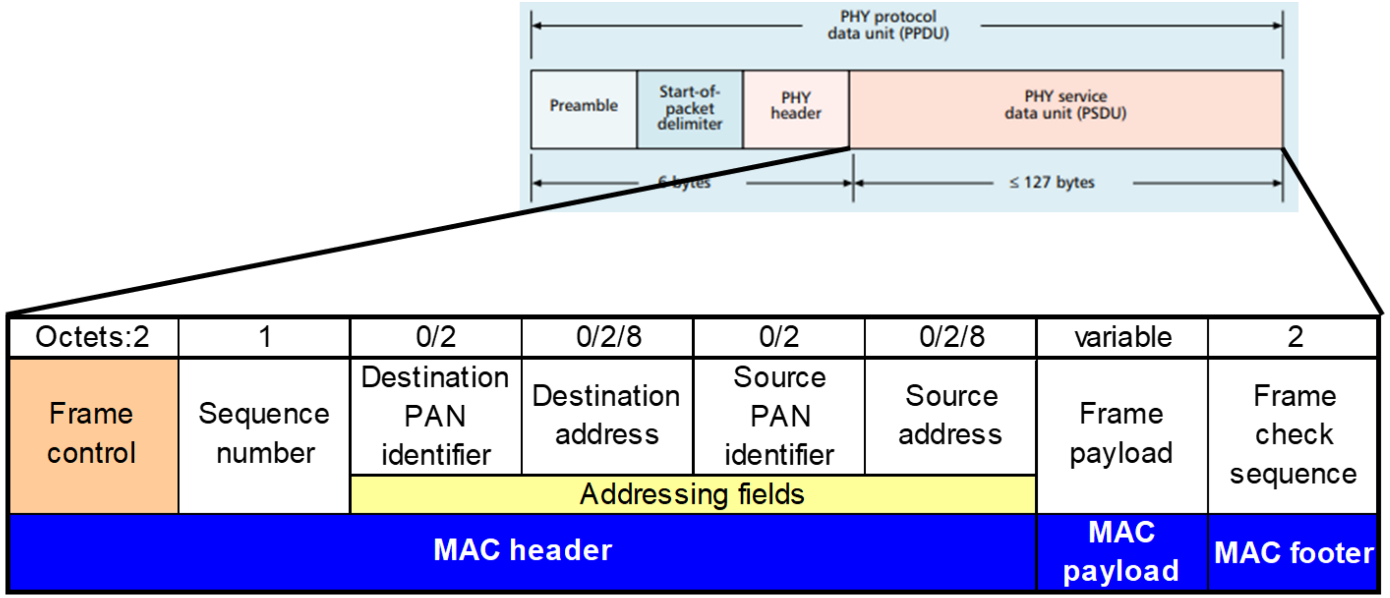
- Non-beacon-enabled PAN only
  - No superframe structure
  - No periodic beacons
  - No Guaranteed Time Slots



- Throw out most existing MAC Commands
  - Network joining will be handled at a higher layer
    - Remove network joining/leaving
    - Remove changing coordinators
    - Remove Guaranteed Time Slot request

Changes to Link Layer and MAC

- Keep unslotted CSMA/CA algorithm
- Keep packet structure
- Keep Frame Types
  - Beacon
  - MAC Command
    - Beacon Request
    - Data Request
  - Data
  - Acknowledgement



Thread networks use a mix of star and mesh topologies

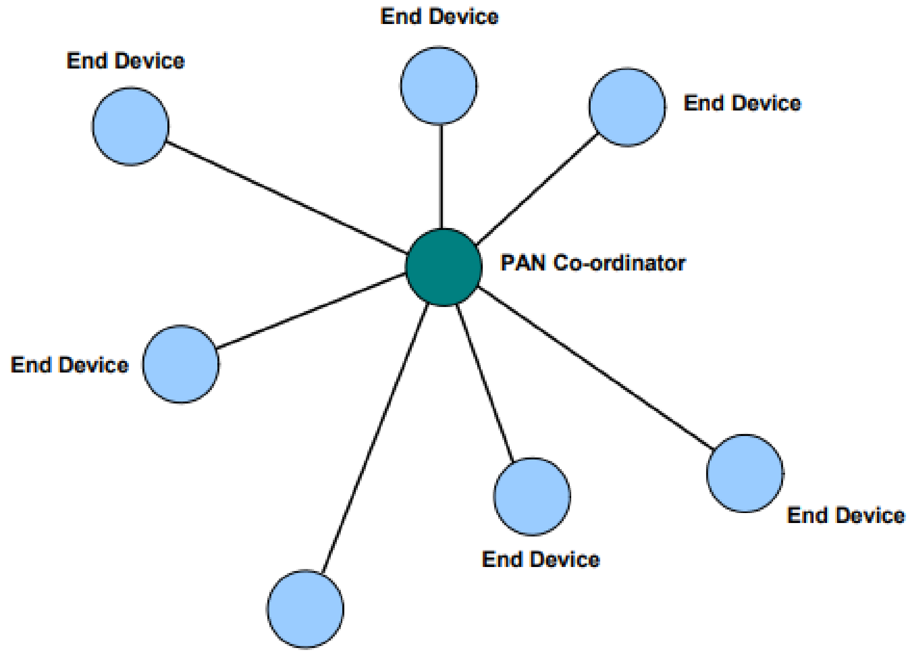


Figure 1: Star Topology

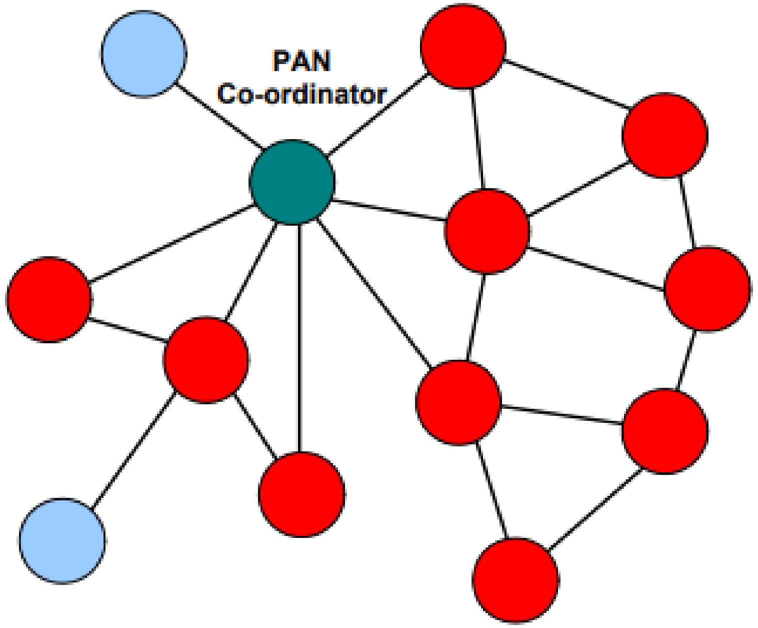


Figure 4: Mesh Topology

Central PAN coordinator in charge of network

- Single point of failure

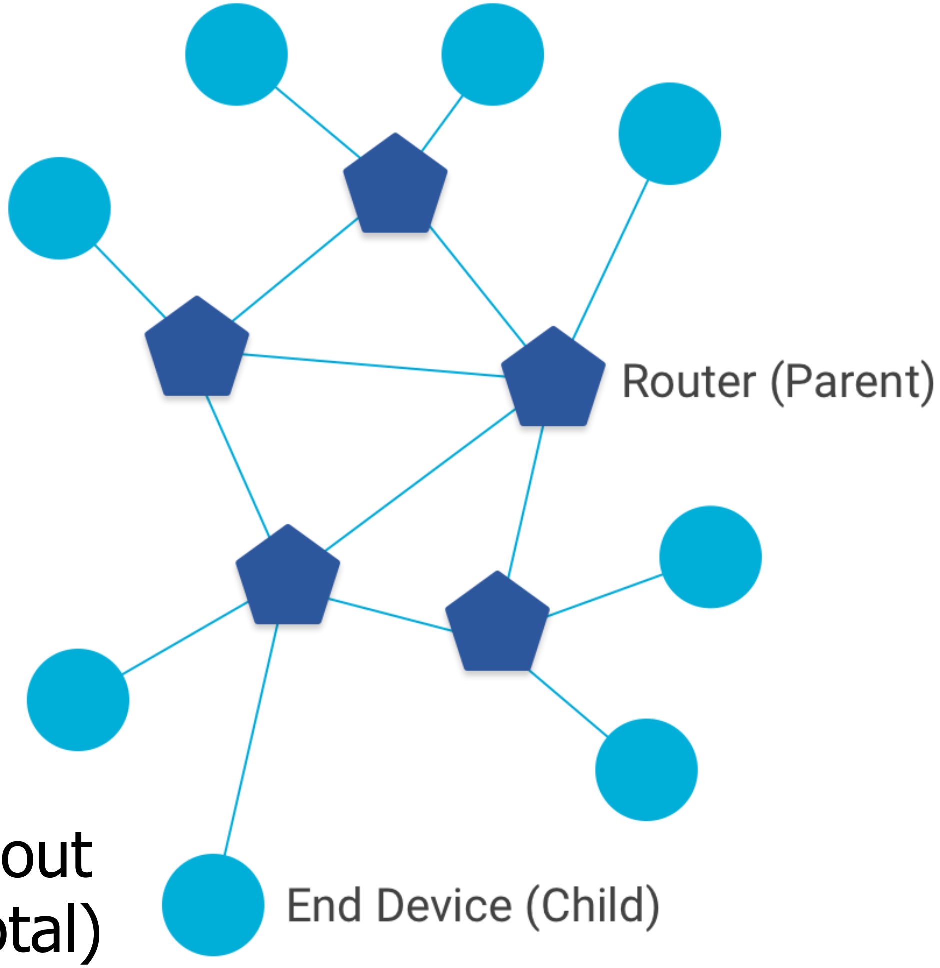
End Devices can be less complicated

PAN Coordinator still in charge
But mid-level Routers add route redundancy
And End Devices didn't have to change at all

Combination of star and mesh topology

- Routers (parent)
  - Mesh communication with other routers
  - Radio always on
  - Forwards packets for network devices
  - Enables other devices to join network
  - Up to 32 routers per network

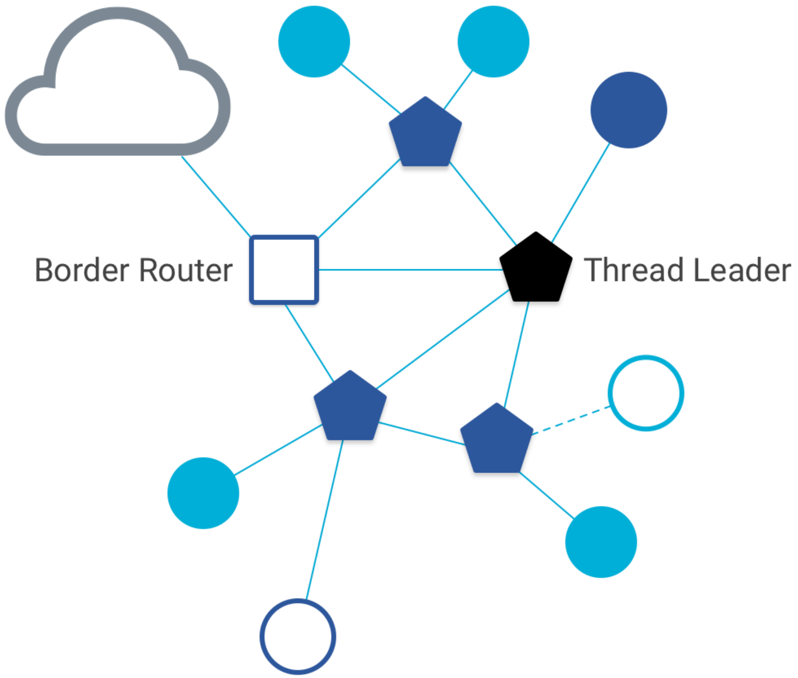
- End devices (child)
  - Communicates with one parent (router)
  - Does not forward packets
  - Can disable transceiver to save power
    - Send packets periodically to avoid timeout
  - Up to 511 end devices per router (~16k total)



Other special roles

- Thread leader
  - Device in charge of making decisions
    - Addresses, Joining details
  - Automatically selected from routers
    - One leader at any given time
    - Additional leader is selected if the network partitions

- Border router
  - Router that also has connectivity to another network
    - Commonly WiFi or Ethernet
  - Provides external connectivity
  - Multiple border routers may exist at once



Why use Thread instead of basic 802.15.4?

- Full specification of upper layers
  - Clarifies how data is transmitted between devices on a network
    - Not just one single hop away
  - Cleans up a lot of things otherwise left implementation-dependent

- Interaction with the world *outside* of the sensor network!
  - Gateway can be a dumb forwarder of packets
  - Devices can directly talk to NTP servers or POST data to a website!

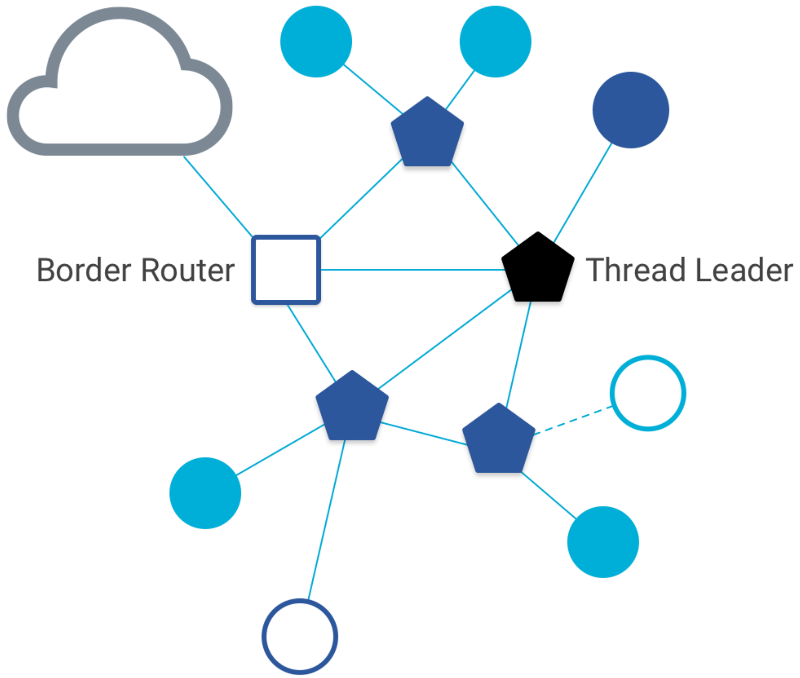
Break + Question

- What kinds of IoT devices are likely to have each thread role?

- End Device

- Router

- Border Router



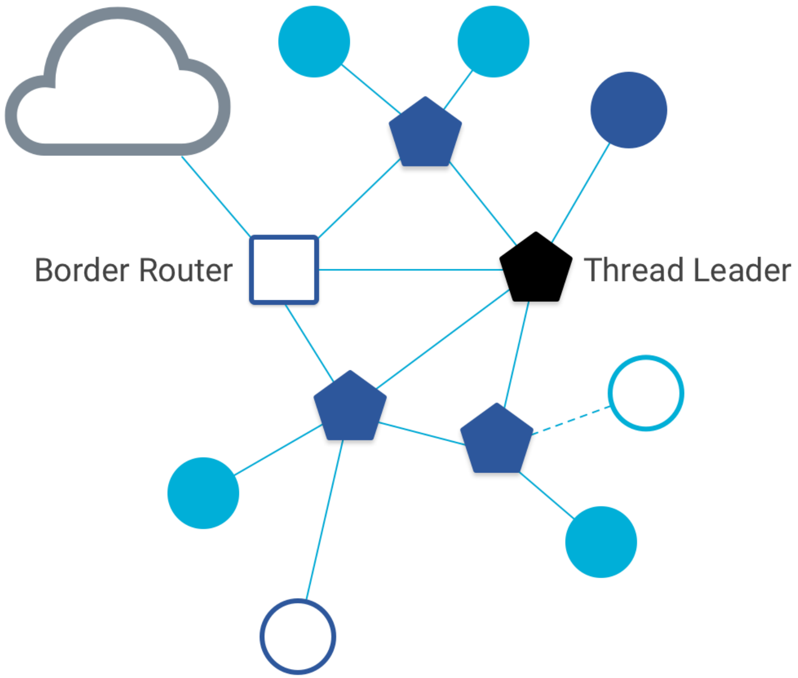
Break + Question

- What kinds of IoT devices are likely to have each thread role?

- End Device
  - Battery-powered sensor
  - Nest Temperature Sensor

- Router
  - Wall-powered device
  - Nest Thermostat

- Border Router
  - Must have Internet connectivity
  - Custom gateway of some type?



Outline

- Thread Overview
- **Thread Addressing**
- Runtime Behavior
- Using IP

Thread uses IPv6 for communication

- Why IP?
  - If Wireless Sensor Networks represent a future of billions of connected devices distributed throughout the physical world
    - Shouldn't they run standard protocols wherever possible?
  - Why IPv6?
    - Clean redesign of IPv4 makes it easier to use to support sensor networks
    - Address structure makes device addresses more compressible

- Benefits
  - Interoperability with normal computers and networks
  - Reuse state of the art developed standards instead of remaking them
    - Security, Naming, Discovery, Services

- Costs
  - Packet overhead can be high (will fix)
  - Complexity for supporting protocols

Hui and Culler, "IP is Dead, Long Live IP for Wireless Sensor Networks". 2008

Background: IPv6

- Replacement to Internet Protocol v4
  - (Something unrelated used version number 5)

- Extended addressing for devices
  - 32-bits for IPv4 addresses -> 128-bits for IPv6 addresses
  - **340 trillion, trillion, trillion** addresses
    - (> 100 times number of atoms on the surface of the Earth)
  - Example: a39b:239e:ffff:29a2:0021:20f1:aaa2:2112

- Supports multiple transmit models
  - Broadcast: one-to-all
  - Multicast: one-to-many
  - Unicast: one-to-one

- Various other improvements

Background: IPv6 address notation rules

- Groups of zeros can be replaced with "::"
  - Can only use "::" in one place in the address
- Leading zeros in a 16-bit group can be omitted

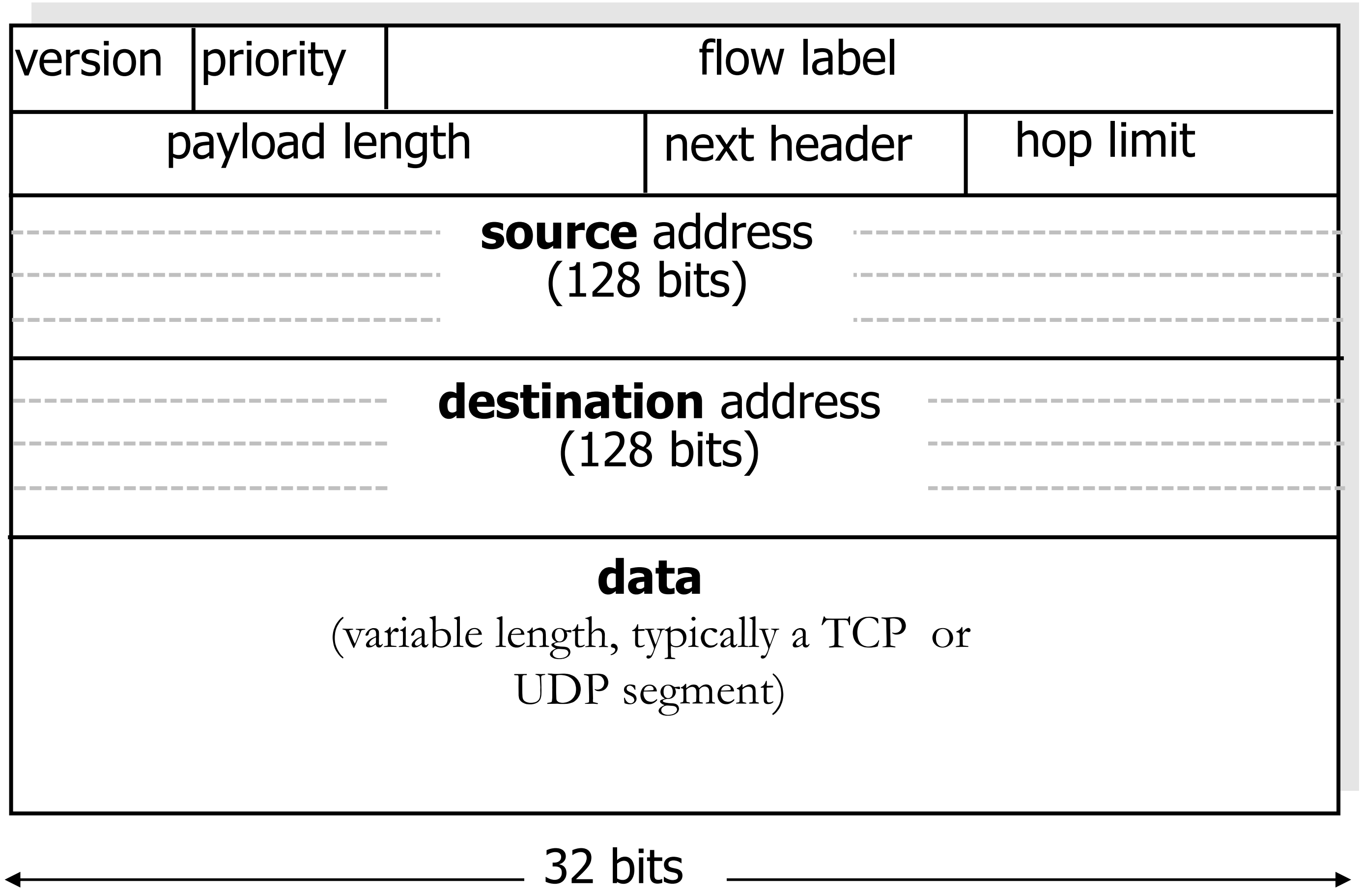
0000:0000:0000:0000:0000:0000:0000:0001 → ::1

2345:1001:0023:1003:0000:0000:0000:0000 → 2345:1001:23:1003::

aecb:0222:0000:0000:0000:0000:0000:0010 → aecb:222::10

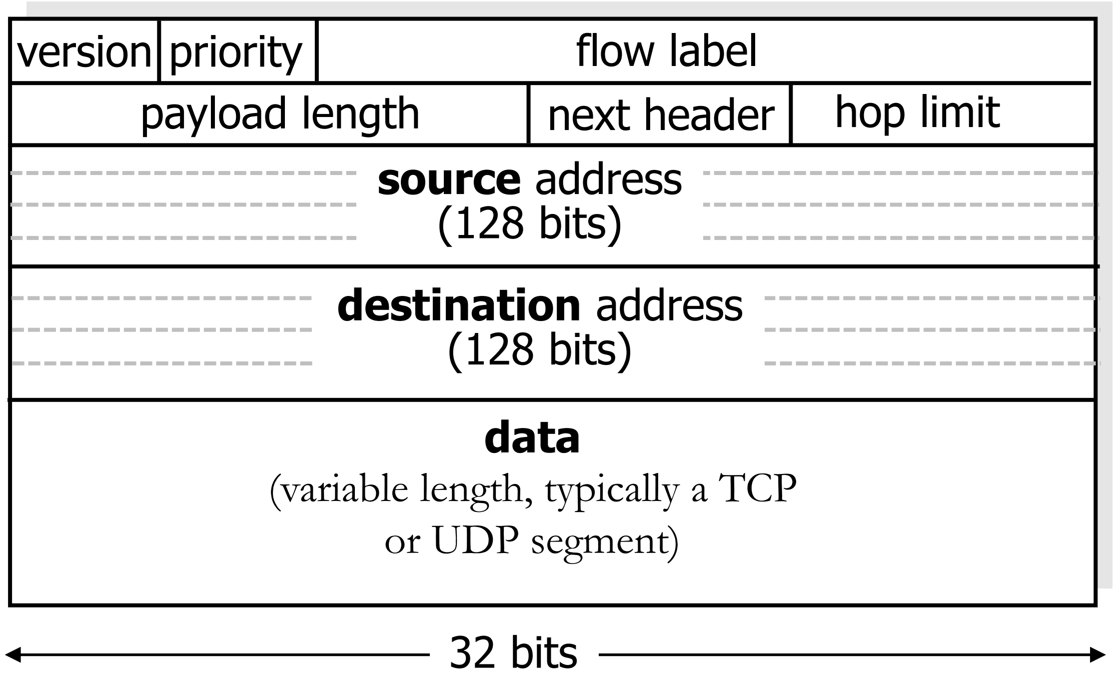
- Special addresses
  - Localhost - ::1 (IPv4 version is 127.0.0.1)
  - Link-Local Network - fe80:: (bottom 64-bits are ~device MAC address)
  - Local Network – fc00:: and fd00::
  - Global Addresses – 2000:: (various methods for allocating bottom bits)

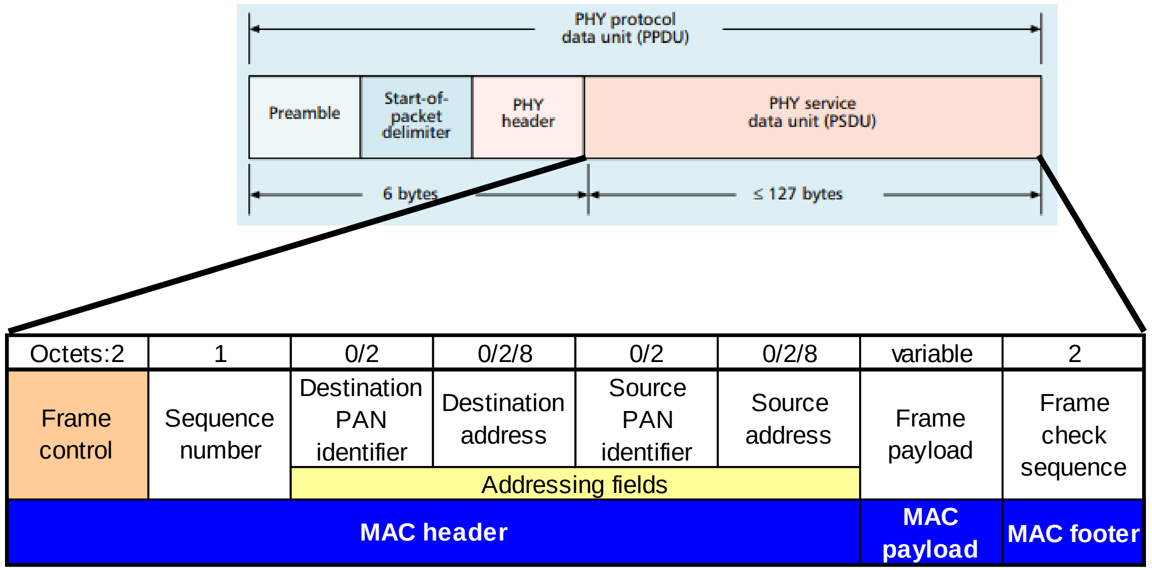
Background: IPv6 datagram format



- Header starts with various data for the router
- **Priority**: like "type of service" in IPv4.
- **Flow label**: marks packets that are part of a transaction for routers
- **Next header**: TCP, UDP, ICMP, etc.
- **Hop limit**: hops to live

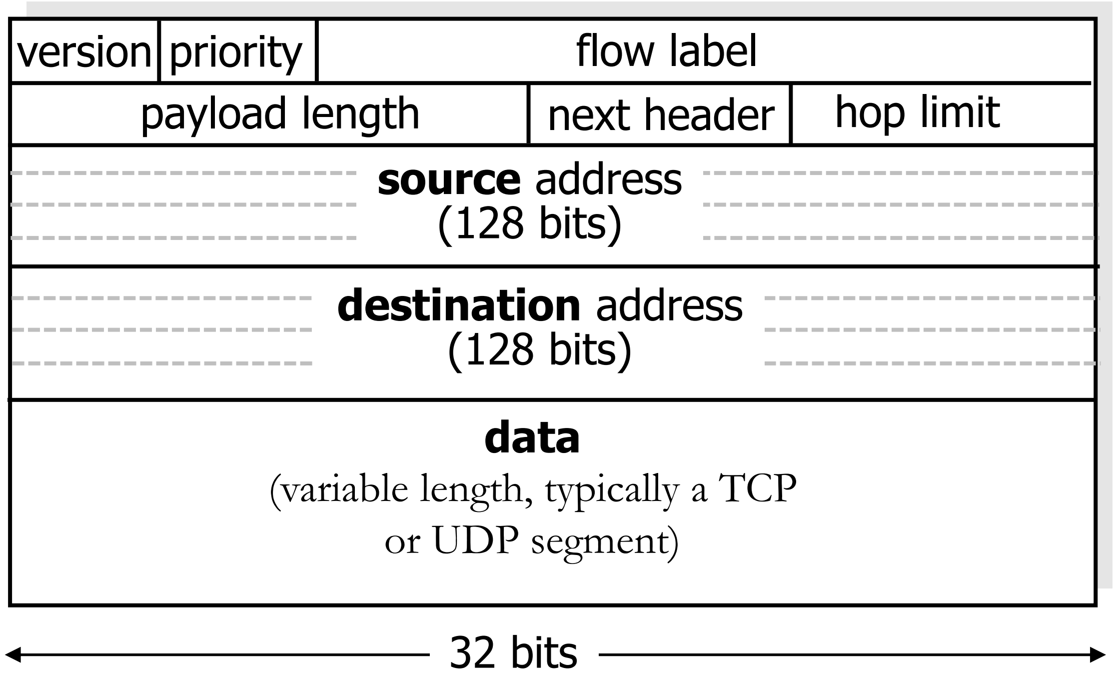
Fitting an IPv6 datagram in an 802.15.4 frame

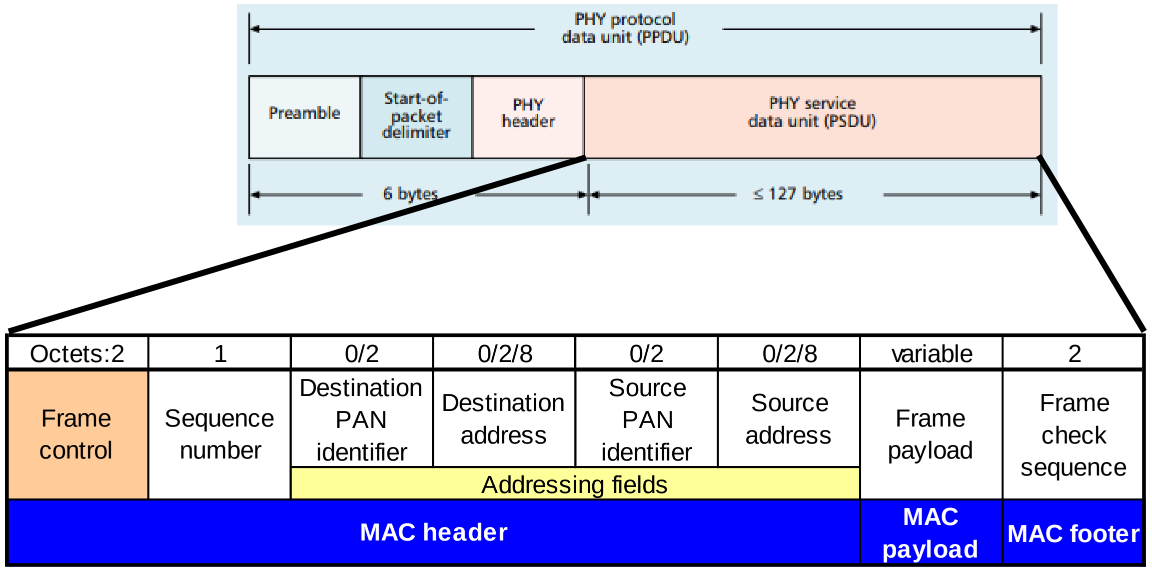




- How many bytes for the IPv6 header?
- How much for the MAC header + footer?
- How much room do we get for payload?

Fitting an IPv6 datagram in an 802.15.4 frame





- How many bytes for the IPv6 header? - 8+16+16 = 40 bytes
- How much for the MAC header + footer? - 5 to 25 bytes depending on options
- How much room do we get for payload? - 127-40-N = 82 to 62 bytes

IPv6 tricky to use directly with 802.15.4

- Header overhead very high
  - around half of bytes in PSDU, even more when security enabled
- IP packets may be large, compared to 802.15.4 max frame size
  - IPv6 requires all links support 1280 byte packets [RFC 2460]

- Need some way to compress and fragment!

6LoWPAN

- Method for running IPv6 over 802.15.4 links
  - IPv**6** over **Lo**w-Power **W**ireless **P**ersonal **A**rea **N**etworks
  - IETF Standard (RFC4944 + updates in RFC6282)

- Directly out of the research world (Jonathan Hui + David Culler)
  - Research Paper: IP is Dead, Long Live IP for Wireless Sensor Networks
  - Thesis of work: sensor networks can and should use IPv6

- Important goals
  - Compress IPv6 headers
  - Handle fragmentation of packets
  - Enable sending packets through mesh

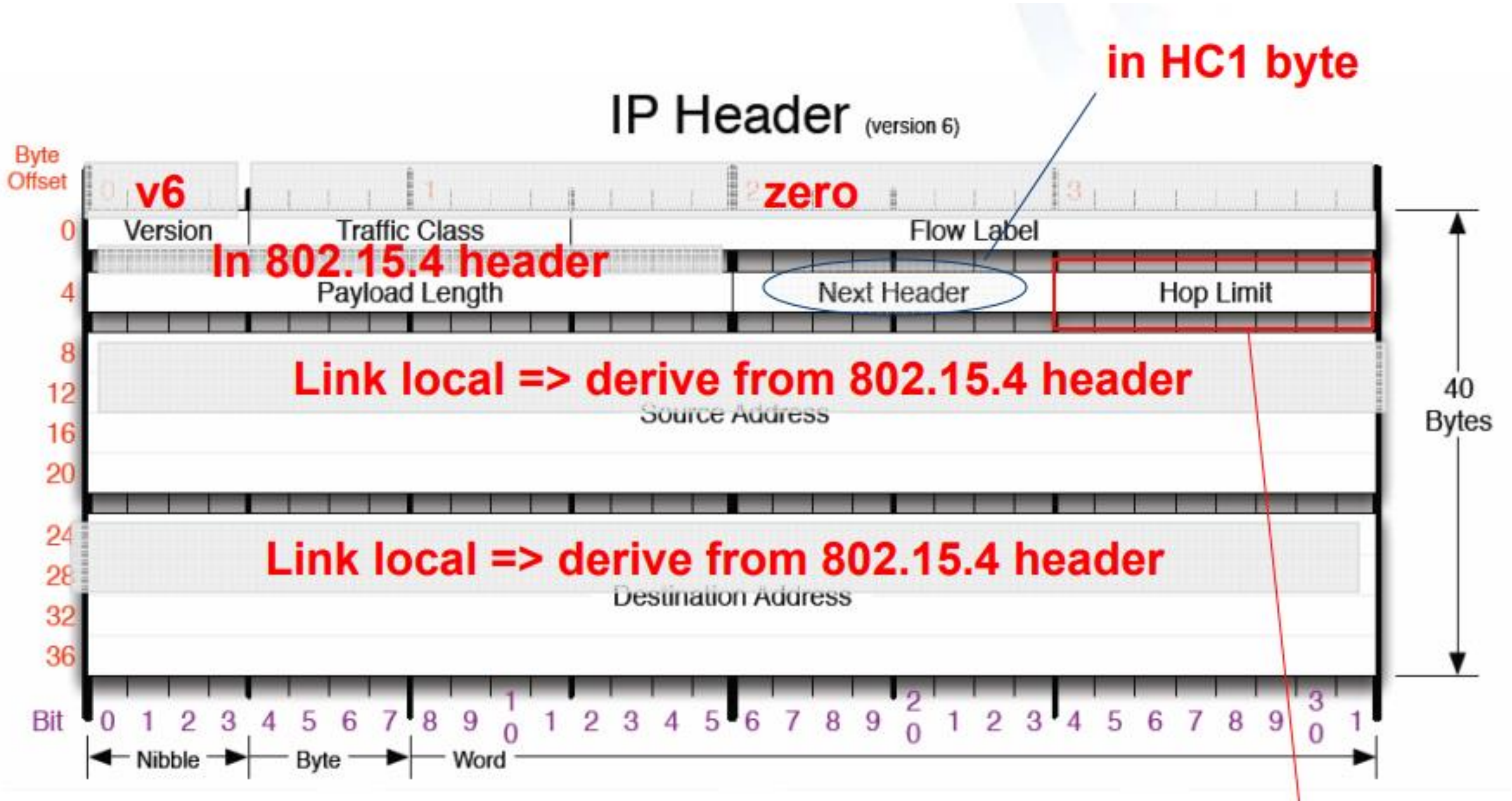
6LoWPAN header compression

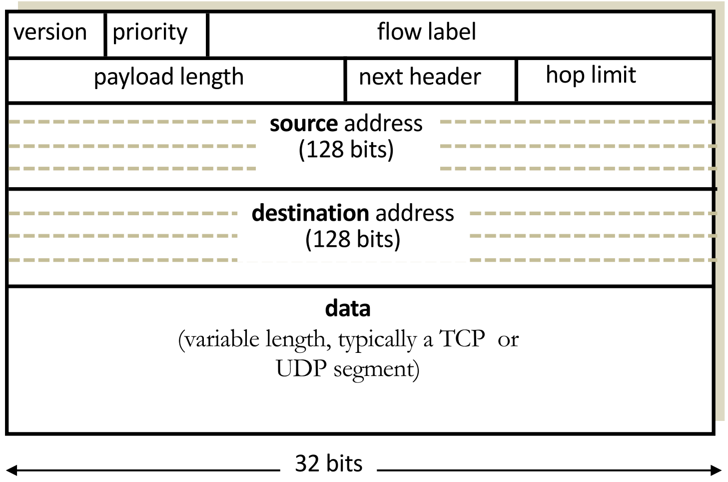
- 40 bytes of IPv6 header are a lot for a 127-byte payload
- Most important goals
  - Communication with devices **inside** the 15.4 network should be low-overhead
  - Communication **outside** of the 15.4 network must be possible
    - Still minimize overhead where possible, but might be larger

- Assume a bunch of common parameters to save space
  - A bunch of options are set to default values
  - Payload length can be re-determined from packet length
  - Source/Destination addresses can often be reassembled from link layer data
    - Plus information about network address assignment known by routers

- Border router "inflates" the packet before sending externally

Example of compression





- http://www.visi.com/~mjb/Drawings/IP_Header_v6.pdf

uncompressed

- Example of HC1 header compression
  - Note: Thread actually uses IPHC from rfc6282 (not HC1), but similar idea
  - Good overview: https://www.youtube.com/watch?v=wRdrCsgJekM

6LoWPAN fragmentation

- Only the first packet of the fragments will hold the IPv6 header
  - Tag, offset, and size are used to reconstruct

Figure 15. First Fragment Header

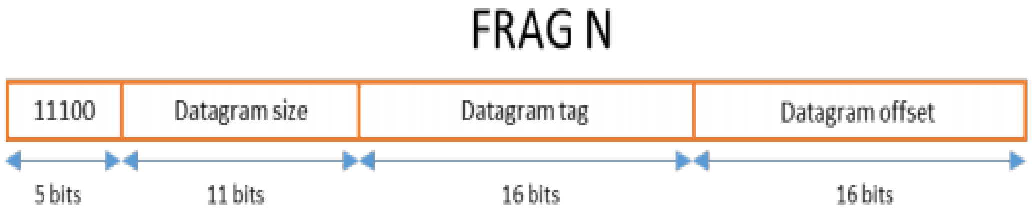


Figure 16. Subsequent Fragment Header

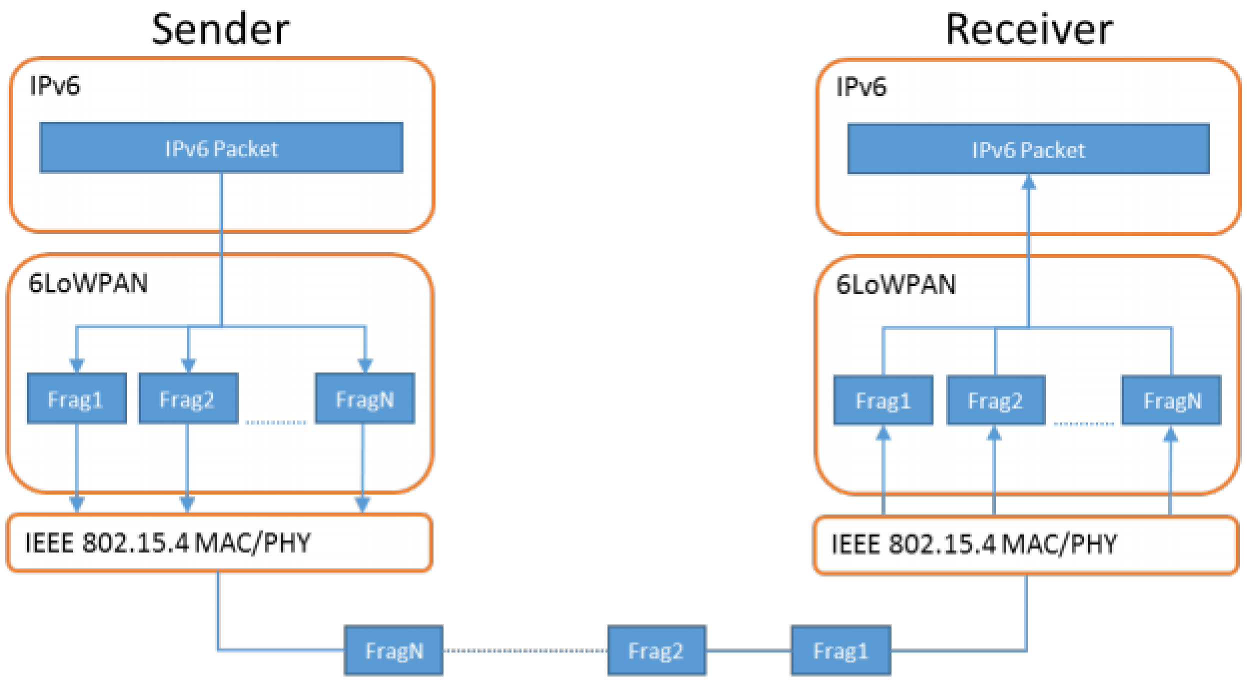


Figure 14. Fragmenting and Reassembling an IPv6 Packet

6LoWPAN mesh forwarding

- Additional header with originator and final addresses

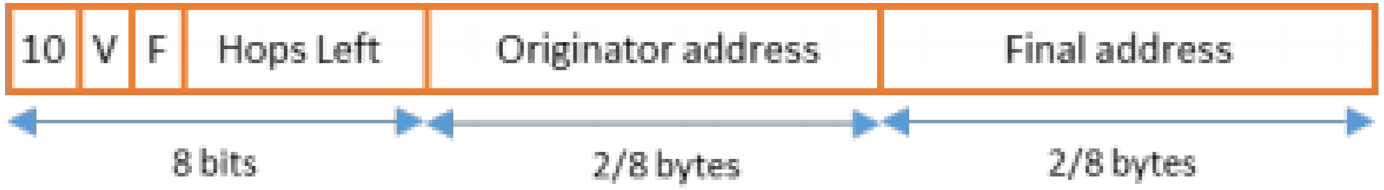


Figure 17. Mesh Header Format

- Which of these headers are used depends on the packet

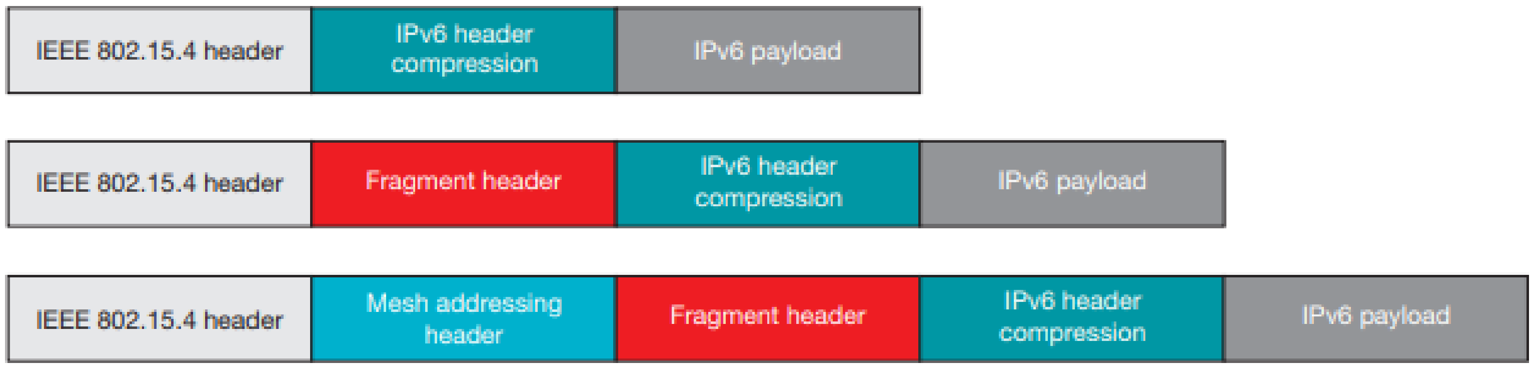


Figure 4. 6LoWPAN stacked headers

Sidebar: IPv6 over BLE

- RFC7668 defines 6LoWPAN techniques for BLE connections

```
         +----------+  +----------------------------+
         |   IPSS   |  |         UDP/TCP/other      |
         +----------+  +----------------------------+
         |   GATT   |  |            IPv6            |
         +----------+  +----------------------------+
         |   ATT    |  |  6LoWPAN for Bluetooth LE  |
         +----------+--+----------------------------+
         |           Bluetooth LE L2CAP             |
    -  - +------------------------------------------+- - - HCI
         |         Bluetooth LE Link Layer          |
         +------------------------------------------+
         |          Bluetooth LE Physical           |
         +------------------------------------------+
```

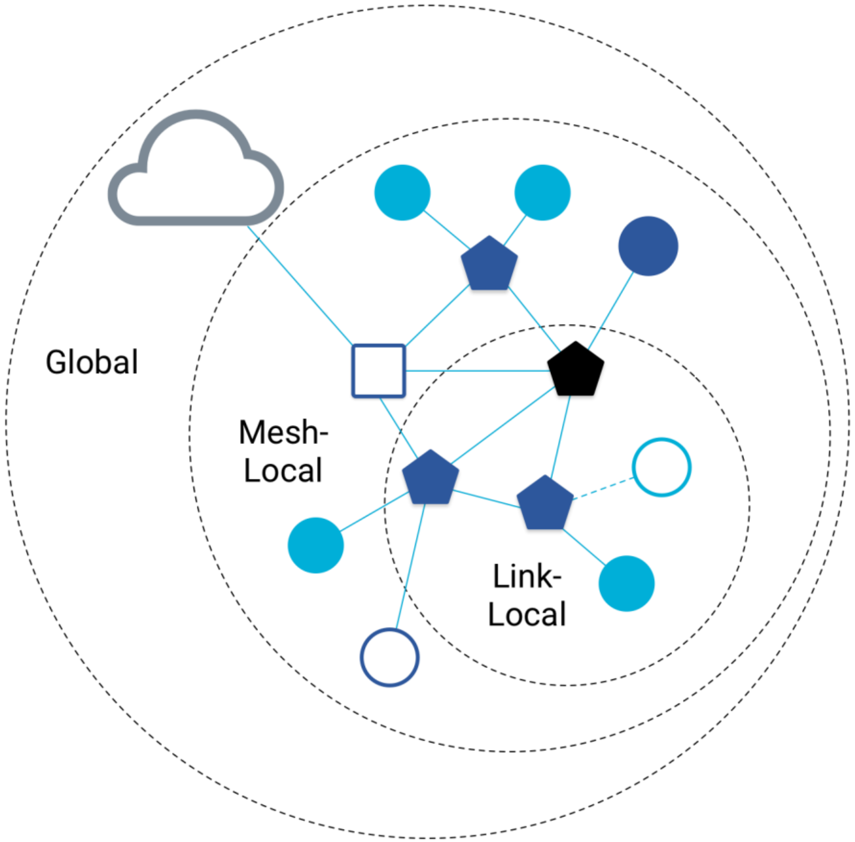
Figure 3: IPv6 and IPSS on the Bluetooth LE Stack

Benefit to IPv6: multiple address spaces per Thread device

- Each device gets an IPv6 address for each way to contact it
  - Global IP address
  - Mesh-local IP address
  - Link-local IP address

  - Topology-based IP address
    - Send to parent
    - Send to child

  - Role-based IP address(es)
    - Send to all Routers
    - Send to Border Router



Traditional addresses in Thread

- Link-Local Addresses
  - FE80::/16
  - Bottommost 64-bits are EUI-64 (MAC address with 0xFFFE in the middle)
  - Permanent for a given device (no matter the network)
  - Used for low-layer interactions with neighbors (discovery, routing info)

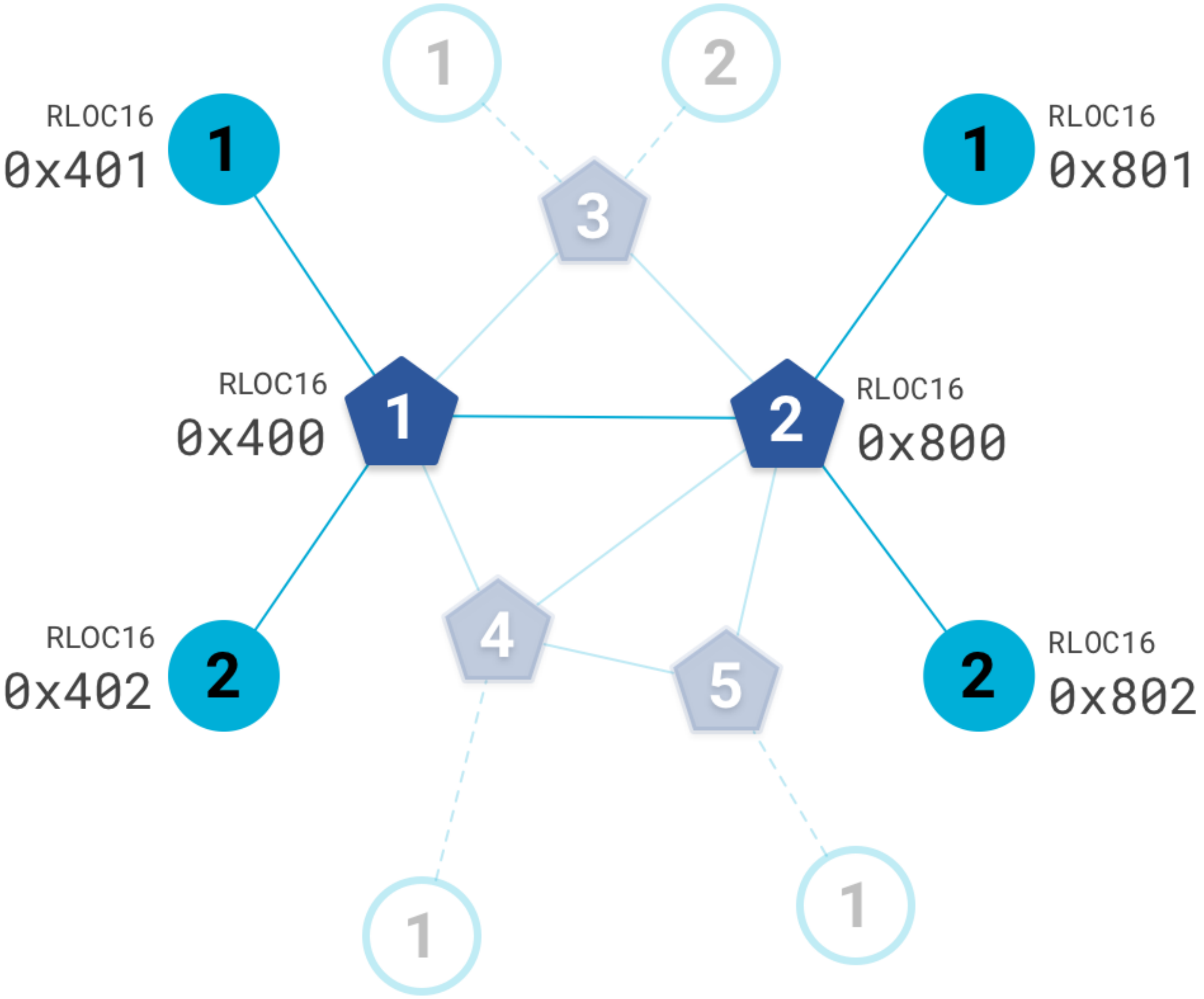
- Mesh-Local Addresses
  - FD00::/8 (FD00:: and FC00:: are for local networks in IPv6)
  - Remaining bits are randomly chosen as part of joining the network
  - Permanent while connection is maintained to a network
  - Used for application-layer interactions

- Global Addresses
  - 2000::/3 (2000:: are for global, unicast IP addresses in IPv6)
  - Public address for communicating with broader internet through Border Router
  - Various methods for allocation (SLAAC, DHCP, Manual)

Topology-based addresses in Thread

- FD00::00FF:FE00:RLOC16
  - Same top bits as mesh-local
- Routing Locator (RLOC)
  - Router ID concatenated with Child ID

- Changes with network topology
  - Used for routing packets



Role-based addresses in Thread

- Multicast
  - FF02::1 – link-local, all listening devices
  - FF02::2 – link-local, all routers/router-eligible
  - FF03::1 – mesh-local, all listening devices
  - FF03::2 – mesh-local, all routers/router-eligible

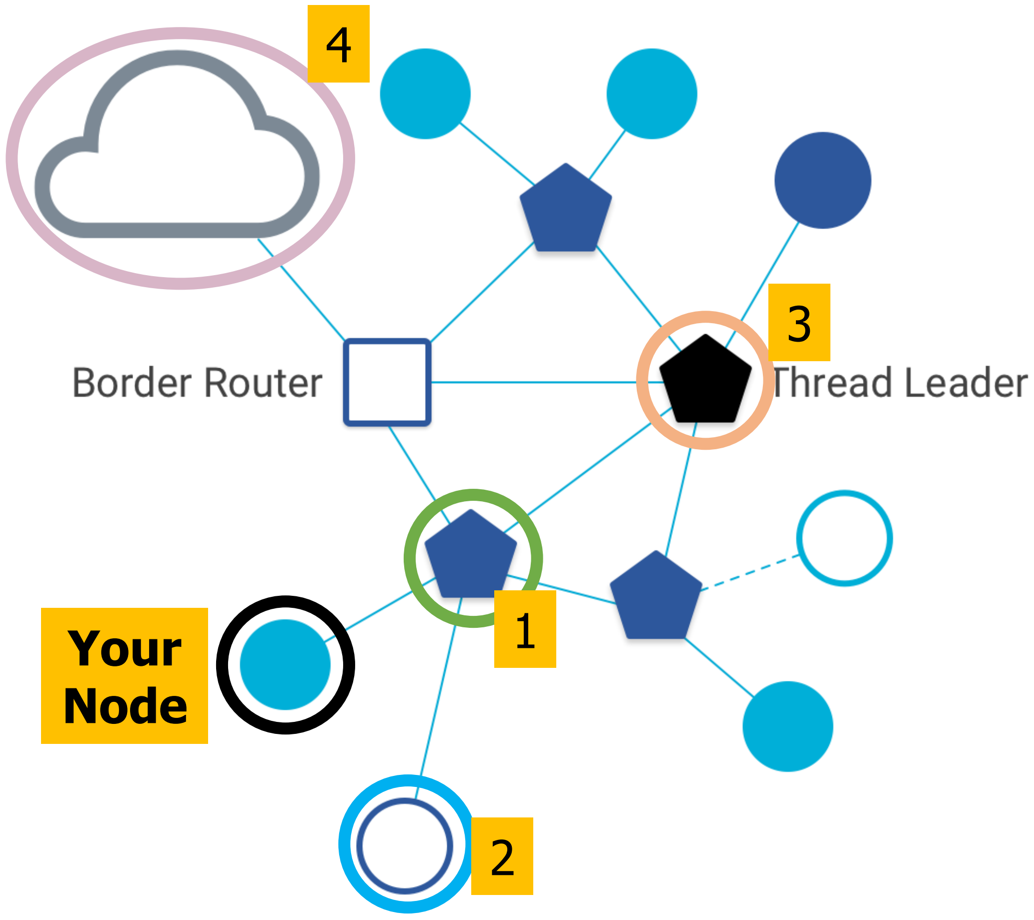
- Anycast
  - FD00::00FF:FE00:FC**xx**
    - 00 – Thread Leader
    - 01-0F – DHCPv6 Agent
    - 30-37 – Commissioner
    - etc.

Break + Question

Which type of address(es) could you use for communication?

1. Global
2. Mesh-local
3. Link-local
4. Topology
5. Role-based

- Communicate with each circled target



Break + Question

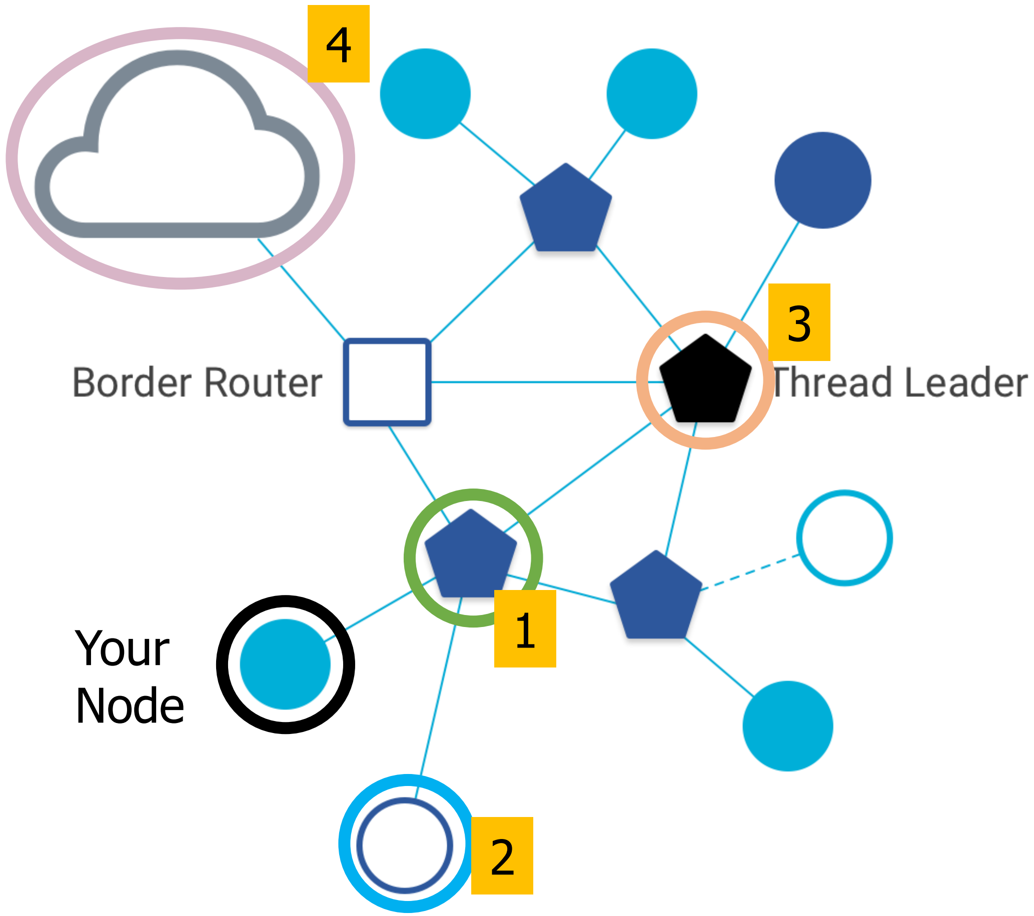
1. Green node
   - Mesh-local
   - Topology (parent)
   - Link-local

2. Blue node
   - Mesh-local
   - Topology (other child of parent)
   - Maybe link-local

3. Orange node
   - Mesh-local
   - Role-based

4. Purple "cloud"
   - Global

Options
1. Global
2. Mesh-local
3. Link-local
4. Topology
5. Role-based

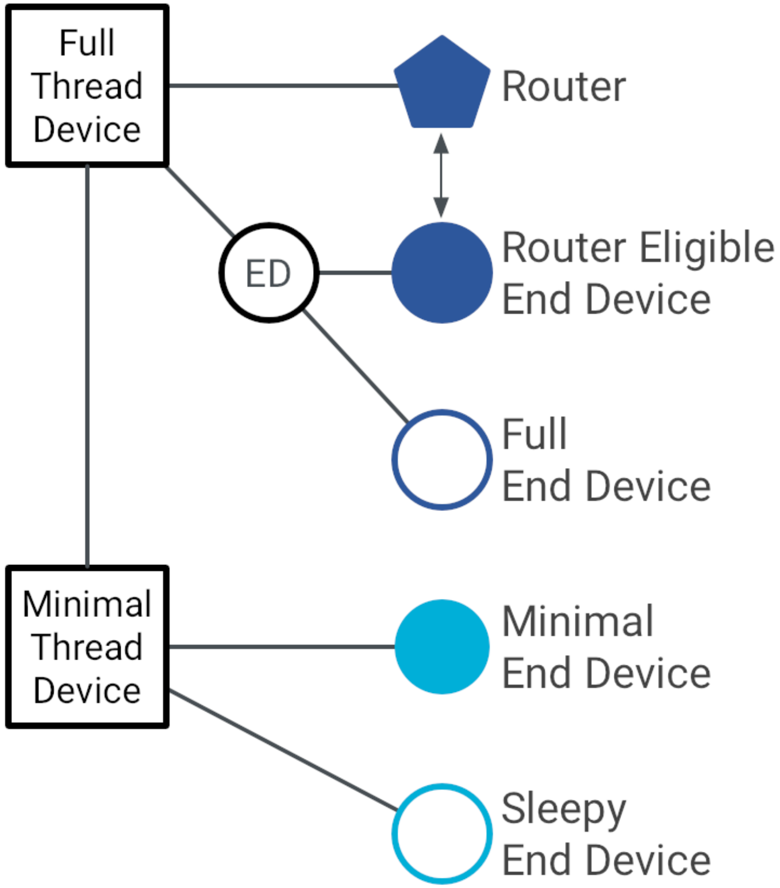


Outline

- Thread Overview
- Thread Addressing
- **Runtime Behavior**
- Using IP

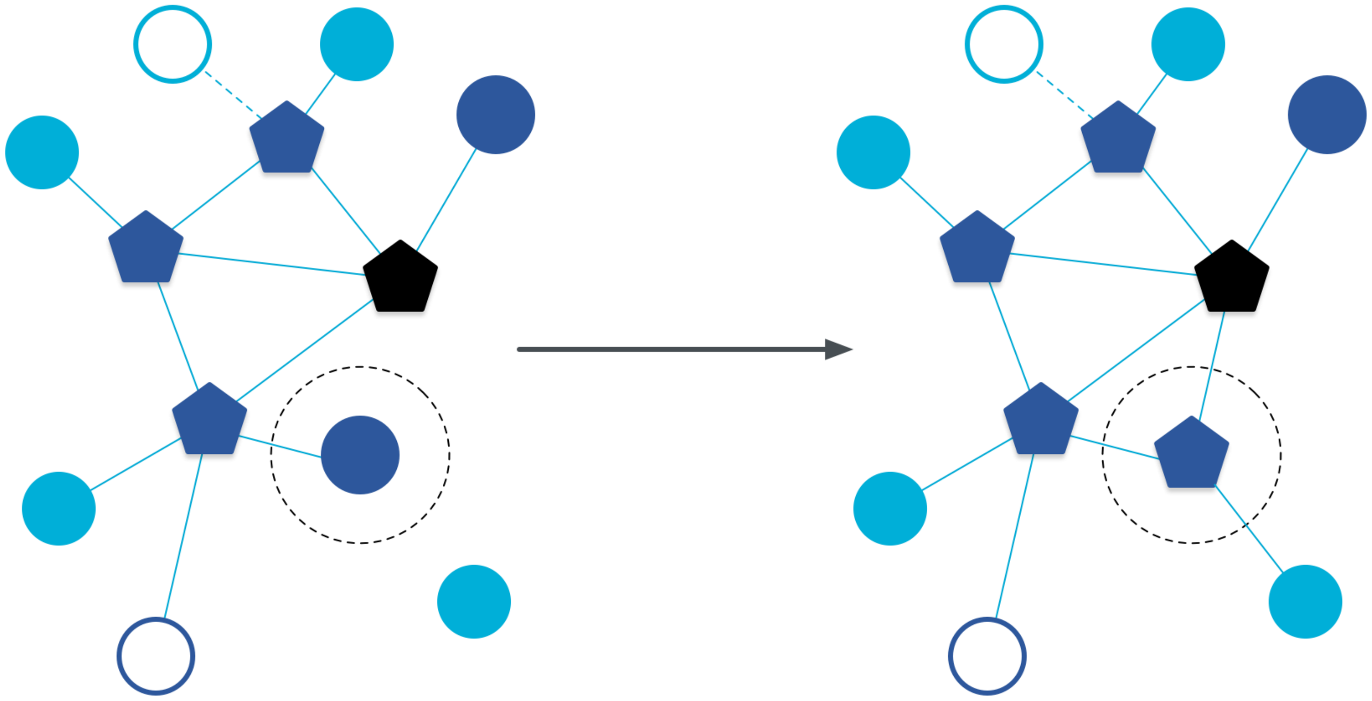
Thread device types

- Full Thread Devices
  - MAC: Always-on
  - Participate in routing
  - Examples:
    - Routers
    - Thread Leader
    - Border Router
    - Router-Eligible End Device (REED)



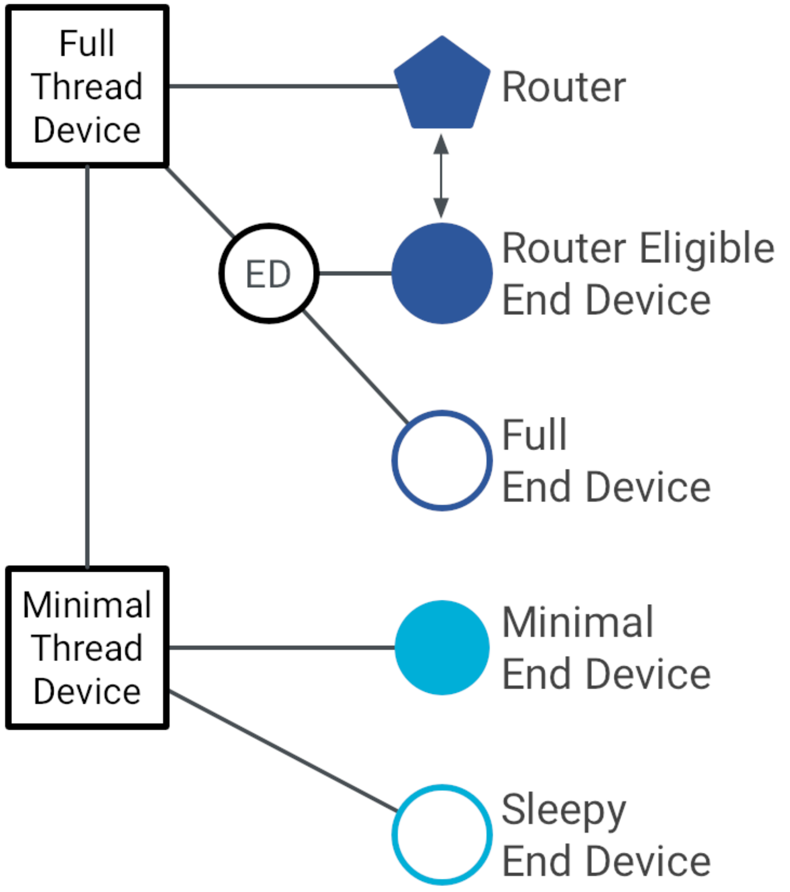
Router promotion

- Router Eligible End Device (REED)
  - A router without any children
  - Can operate as an end device with one connection (lower power)
  - Promotes to a router when a joining end device relies on it
    - If there is room for an additional router (max 32, typical 16-23)



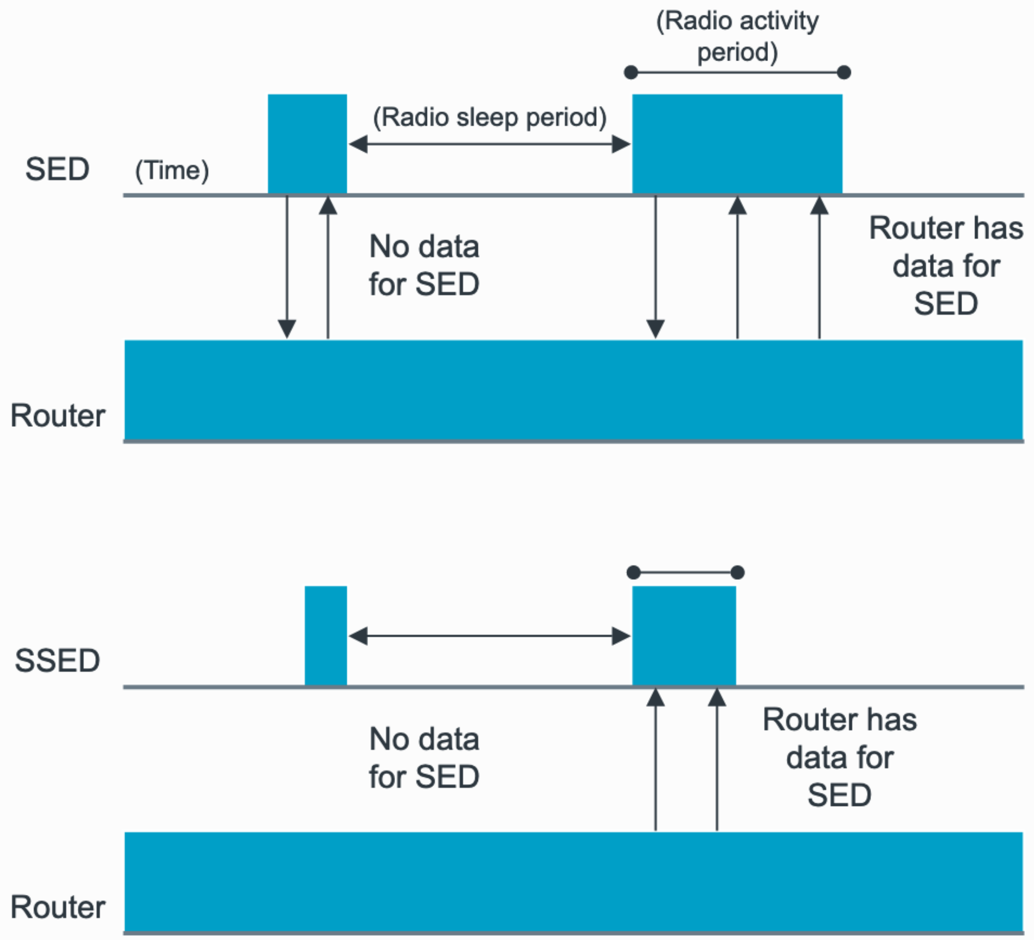
Thread device types

- Full Thread Devices
  - MAC: Always-on
  - Participate in routing
  - Examples:
    - Routers
    - Thread Leader
    - Border Router
    - Router-Eligible End Device (REED)
- Minimal Thread Devices
  - MAC: Can be low power
  - Only send/receive to/from parent
  - Examples:
    - Minimal End Device (MED)
    - Sleepy End Device (SED)
    - Synchronized Sleepy End Device (SSED)



Sleepy End Devices

- These are the low power devices
- Periodically must exchange messages with Router
- Sleepy End Device (SED)
  - MAC:
    - TX: Router always-on, so send as needed (ALOHA)
    - RX: Periodically check in with router if new data pending
- Synchronized Sleep End Device (SSED)
  - MAC:
    - TX: ALOHA
    - RX: Listen during pre-configured windows



Comparison of Thread SED and Thread SSED radio activity

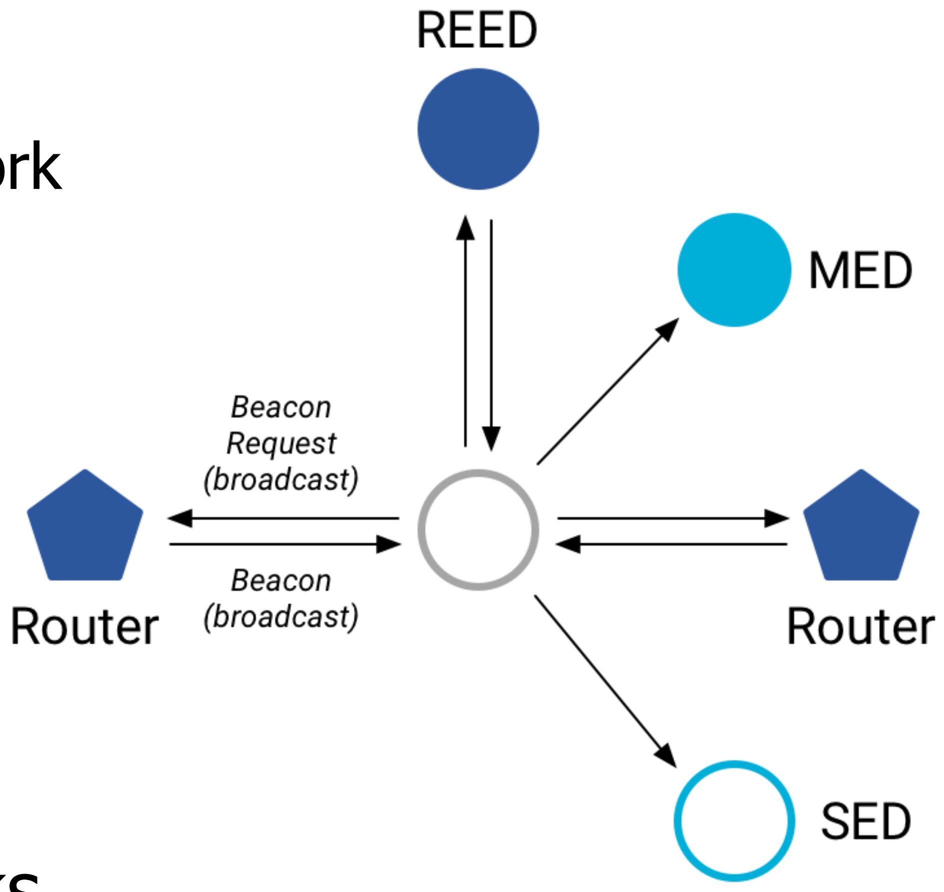
https://developer.nordicsemi.com/nRF_Connect_SDK/doc/latest/nrf/protocols/thread/sed_ssed.html

Discovering Thread networks

- "Beacon Request" MAC command
  - Routers/Router-eligible devices respond
  - Payload contains information about network

- Thread network specification
  - PAN ID – 16-bit ID
  - XPAN ID – extended 64-bit ID
  - Network Name – human-readable

- Active scanning across channels can quickly find all existing nearby networks



Creating a new network

- Select a channel (possibly by scanning for availability)
- Become a router
  - Elect yourself as Thread Leader
  - Respond to Beacon Requests from other devices
- Further organization occurs through Mesh-Level Establishment protocol

Mesh-Level Establishment (MLE)

- Creating and configuring mesh links
  - Payloads placed in UDP packets within IPv6 payloads
- Commands for mesh
  - Establish link
  - Advertise link quality
  - Connect to parent

0	Command Type	TLV	…	TLV

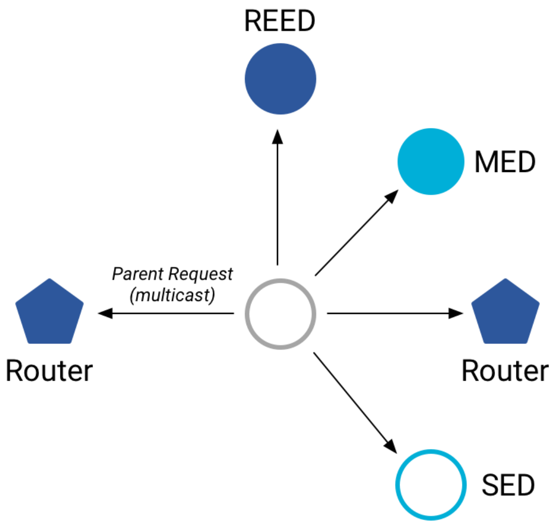
OR (secure version)

255	Aux Header	Command Type	TLV	…	TLV	MIC

- TLVs (Type-Length-Value)
  - Various data types that may be helpful within those packets
  - Addresses, Link Quality, Routing Data, Timestamps

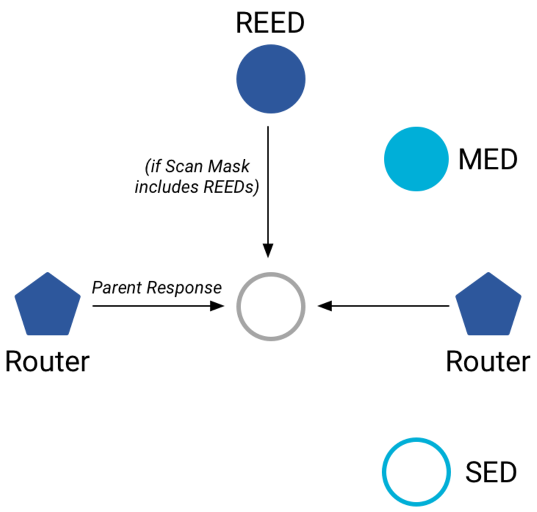
Joining an existing network

- All devices join as a child of some existing router



1. Send a Parent Request (to all routers/router-eligible)
   - Using the multicast, link-local address

2. Receive a Parent Response (from all routers/router-eligible separately)
   - Contains information on link quality

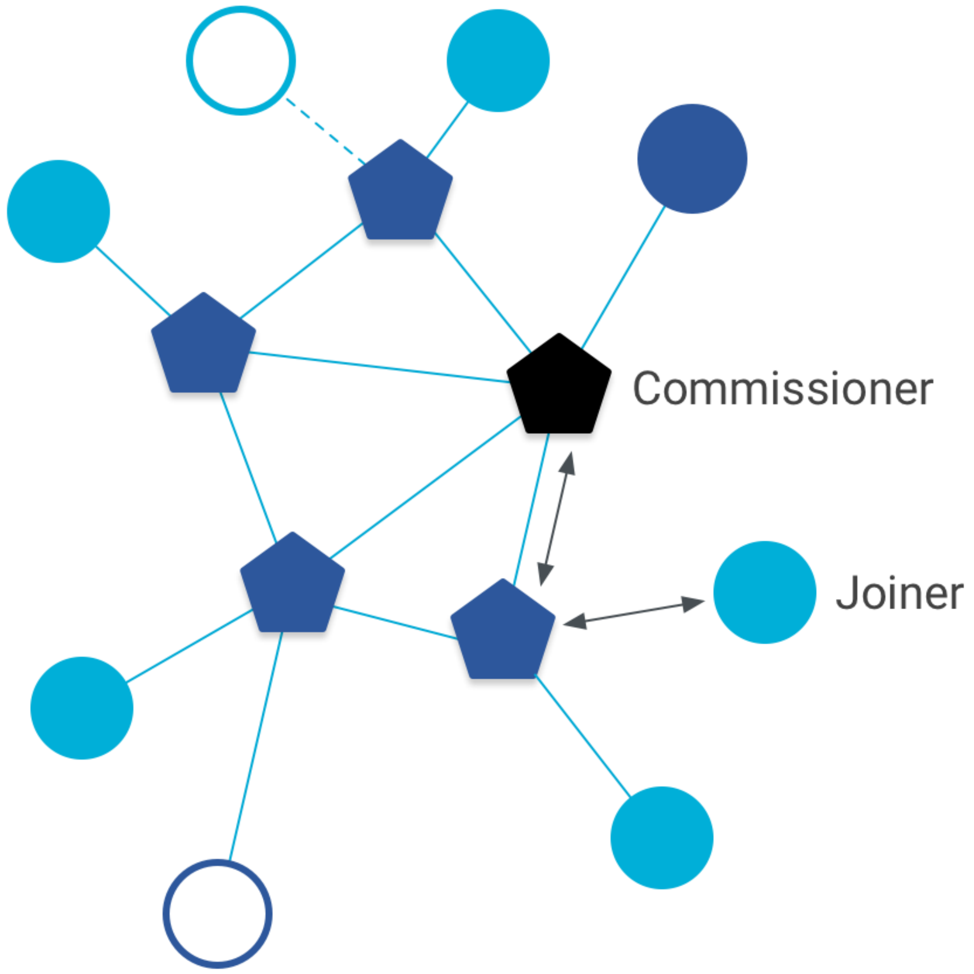


3. Send a Child ID Request (to router with best link)
   - Contains parameters about the new child device

4. Receive a Child ID Response (from that router)
   - Contains address configurations

Thread Commissioning

- As part of joining a network, a thread device is also “commissioned”
- Bonus step in the joining process for real-world networks
- Authenticates the joining device allowing it to join and encrypt communications



https://www.threadgroup.org/Portals/0/documents/support/CommissioningWhitePaper_658_2.pdf

Updates to Thread specification

- Thread version 1.2
    - Simpler, lower-power end devices
        - Any packet sent is enough to keep the device attached to network
        - All acknowledgements identify if packets are available for it
    - Power control
        - Reduce transmission power to minimum needed for “good connection”
        - Reduces potential for “hidden terminal problem”

- Thread version 1.3
    - Better IPv6 support
        - Coordinate address selection with IP network boarder router connects to
        - Shuttle DNS Service Discovery messages between networks
    - Support for TCP

Outline

- Thread Overview
- Thread Addressing
- Runtime Behavior
- **Using IP**

Communicating with IP

- Any communication that layers on top of IP is now possible
  - If there is a library to support it

- Common choices
  - UDP
    - DNS – translate hostnames into IP addresses
    - SNTP – get real-world time, accuracy better than 1 second
    - CoAP – send and receive data

Constrained Application Protocol - CoAP

- HTTP, but over UDP targeting less-capable devices
  - Same REST architecture
  - Adds capability for automatic retransmissions

- CoAP Requests
  - Have a type: GET, POST, PUT, DELETE
  - Have a URL: /file/etc
  - Have data up to 65 KB

Sensor networks don't use TCP (yet?)

- Uncommon choice: TCP
  - Concerns: Too large, too slow, poorly suited to lossy networks
  - Also concerning: We're just replicating TCP poorly

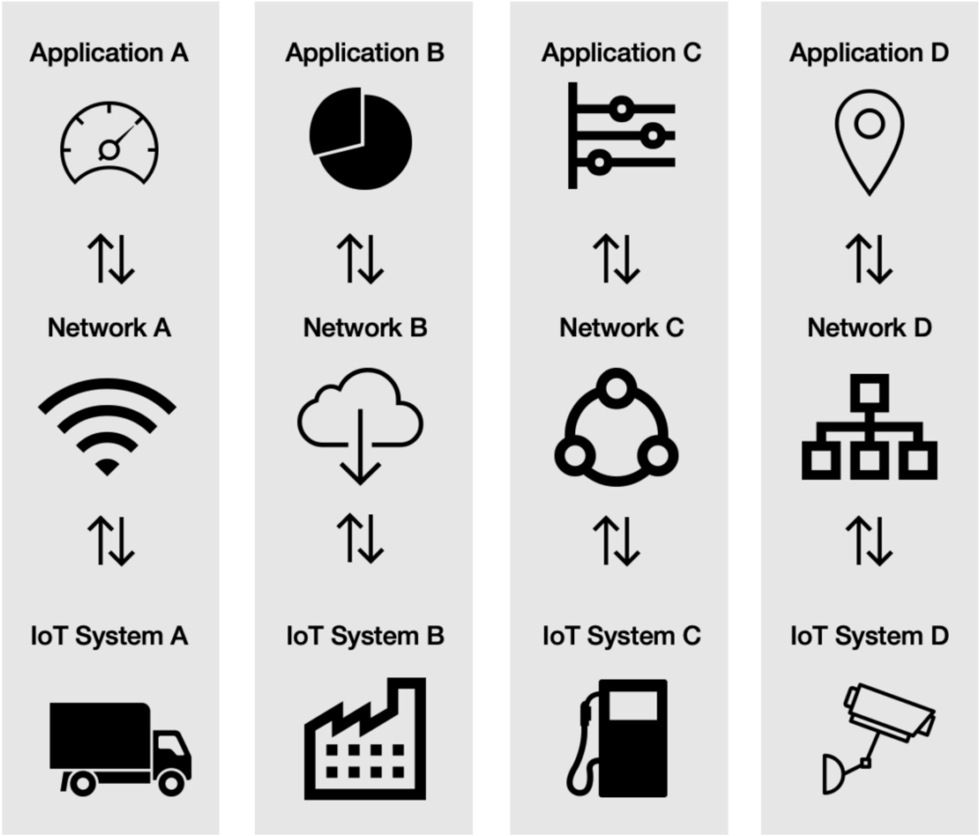
  - Active research:
    - Sam Kumar, Michael Anderson, Hyung-Sin Kim, David Culler. "Performant TCP for Low-Power Wireless Networks". 2020.

    - The debate is still very much open

- 2023 update: Thread now supports TCP!!
  - Primarily for large data payloads, like firmware updates

A problem: the siloed internet of things

- Problem: companies are more interested in selling you the whole stack
  - Which then makes it harder for devices to be interoperable
- This is not Thread or IP-specific, but a problem all IoT devices are facing
- Concerns
  - What IP address do you send data to?
  - Manufacturer's server is an obvious choice
- We'll talk about the Matter standard as an approach to this issue



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