Wireless Sensor Networks: 6LowPAN&RPL

Sedat Görmüş, PhD

Source presentations :

1. Jurgen Schonwalder, Internet of Things: 802.15.4, 6LoWPAN, RPL, COAP
2. Siarhei Kuryla, RPL: IPv6 Routing Protocol for Low power and Lossy Networks

Outline

- IEEE 802.15.4
  - Radio Characteristics & Topologies
  - Frame Formats, MAC, Security
- IPv6 over IEEE 802.15.4 (6LowPAN)
  - Header Compression
  - Fragmentation and Reassembly
- RPL: IPv6 Routing for LLNs
  - Instances, DODAGs, Versions, Ranks
  - DODAG Construction and RPL ICMPv6 Messages

802.15.4 Evolution

802.15.4-2003

Original version using Direct Sequence Spread Spectrum (DSSS) with data transfer rates of 20 and 40 kbit/s

802.15.4-2006

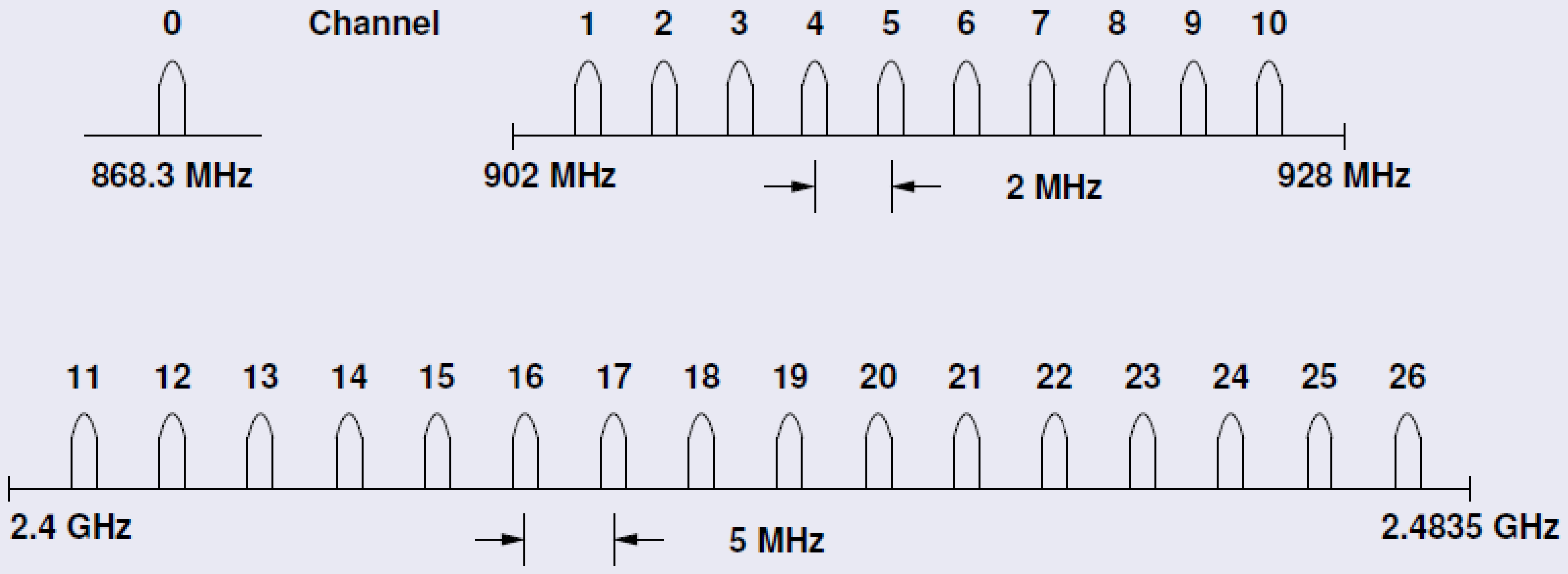
Revised version using Direct Sequence Spread Spectrum (DSSS) with higher data rates and adding Parallel Sequence Spread Spectrum (PSSS)

802.15.4a-2007

Adding Direct Sequence Ultra-wideband (UWB) and Chirp Spread Spectrum (CSS) physical layers to the 2006 version of the standard (ranging support)

Radio Characteristics

Frequencies and Data Rates



Frequency	Channels	Region	Data Rate	Baud Rate
868-868.6 MHz	0	Europe	20 kbit/s	20 kBaud
902-928 MHz	1-10	USA	40 kbit/s	40 kBaud
2400-2483.5 MHz	11-26	global	250 kbit/s	62.5 kBaud

Device Classes Recap

- **Full Function Devices (FFDs)**
  - Any topology
  - Can be a PAN coordinator
  - Talks to any other device
  - Implements complete protocol set

- **Reduced Function Devices**
  - Reduced protocol set
  - Very simple implementation
  - Not a PAN coordinator
  - Limited to leaf nodes in complex topologies

Some Definitons

Network Device

An RFD or FFD implementation containing an IEEE 802.15.4 medium access control and physical interface to the wireless medium.

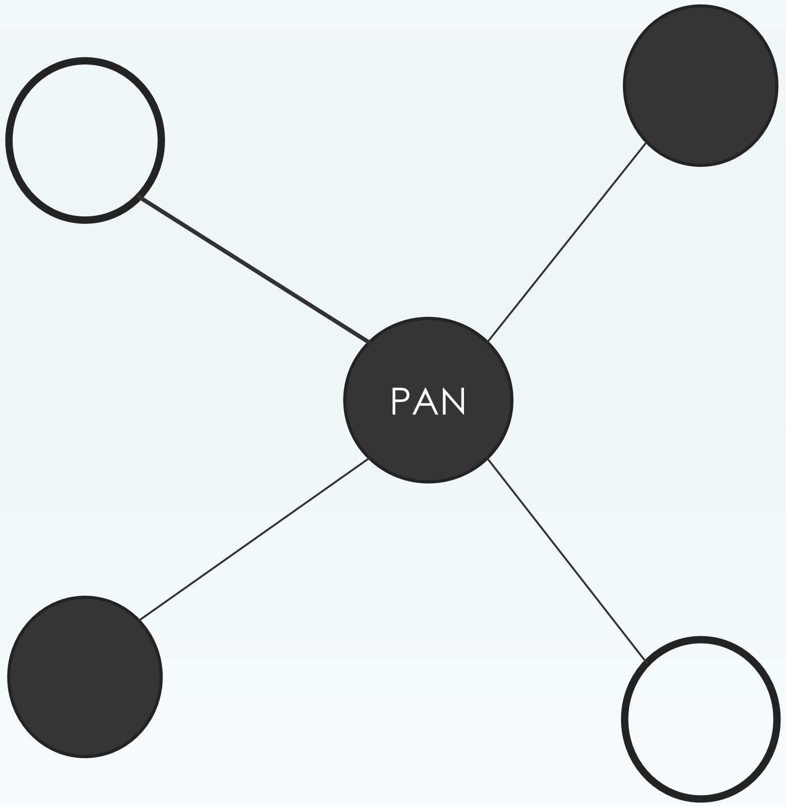
Coordinator

An FFD with network device functionality that provides coordination and other services to the network.

PAN Coordinator

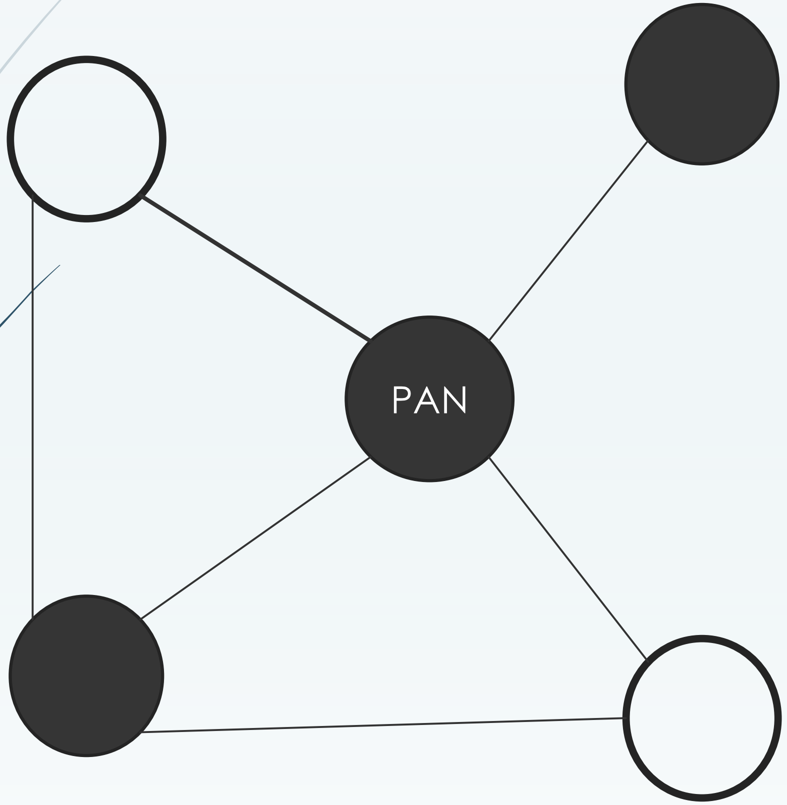
A coordinator that is the principal controller of the PAN. A network has exactly one PAN coordinator.

Star Topology



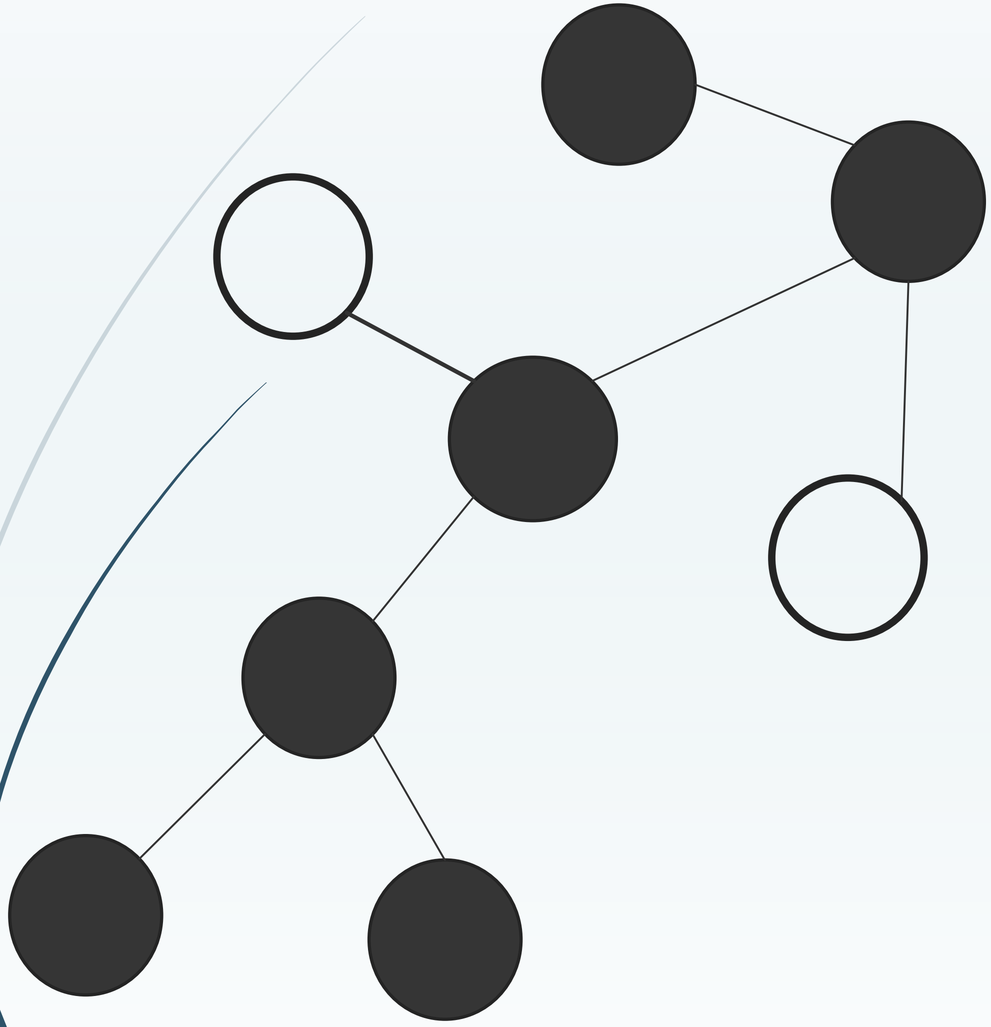
- All nodes connec to PAN coordinator.
- Leafs maybe any combination FFD or RFD
- PAN coordinator shall have reliable power source.

P2P topology



- Nodec can coomunicate either through the PAN coordinator or point to point links
- Extension of star topology

Cluster Tree Topology



- LEAF nodes connect to FFDs.
- One of the FFDs serve as the PAN coordinator
- Clustered Star topologies forms one of the most popular use-case

Frame Formats

General Frame Format

octets: 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 sequence check

bits: 0–2	3	4	5	6	7–9	10–11	12–13	14–15
Frame type	Security enabled	Frame pending	Ack. requested	Intra PAN	Reserved	Dst addr mode	Reserved	Src addr 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 octets; max. frame header 25 octets

Media Access Control

Carrier Sense Multiple Access / Collision Avoidance

Basic idea of the CSMA/CA algorithm:

- First wait until the channel is idle.
- Once the channel is free, start sending the data frame after some random backoff interval.
- Receiver acknowledges the correct reception of a data frame.
- If the sender does not receive an acknowledgement, retry the data transmission.

Unslotted Mode

Node $\longrightarrow$ PAN, Node $\longrightarrow$ Node

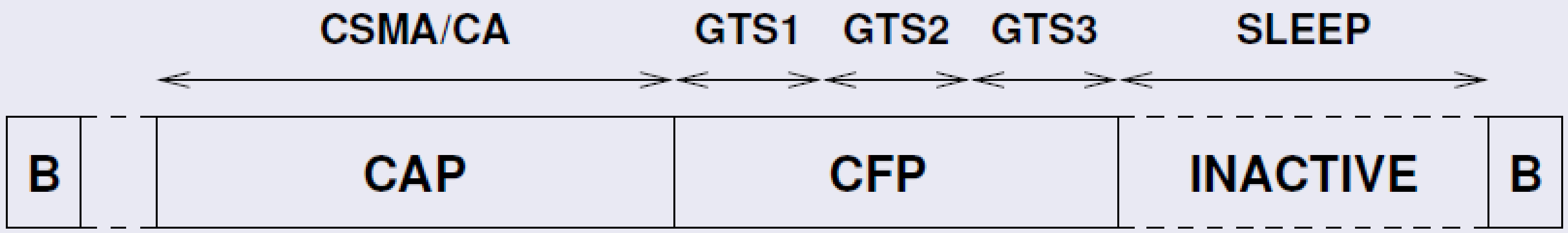
- The sender uses CSMA/CA and the receiver sends an ACK if requested by the sender.
- Receiver needs to listen continuously and can't sleep.

PAN $\longrightarrow$ Node

- The receiver polls the PAN whether data is available.
- The PAN sends an ACK followed by a data frame.
- Receiving node sends an ACK if requested by the sender.
- Coordinator needs to listen continuously and can't sleep.

Slotted Mode

Superframes



- A superframe consists of three periods:
  1. During the Contention-Access-Period (CAP), the channel can be accessed using normal CSMA/CA.
  2. The Contention-Free-Period (CFP) has Guaranteed Time Slots (GTS) assigned by the PAN to each node.
  3. During the Inactive-Period (IP), the channel is not used and all nodes including the coordinator can sleep.
- The PAN delimits superframes using beacons.

Security

Security Services

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

- Key management must be provided by higher layers
- Implementations must support AES-CCM-64 and Null

IPv6 over 802.15.4 (6LowPAN)

Benefits of IP over 802.15.4 (RFC 4919)

1. The pervasive nature of IP networks allows use of existing infrastructure.
2. IP-based technologies already exist, are well-known, and proven to be working.
3. Open and freely available specifications vs. closed proprietary solutions.
4. Tools for diagnostics, management, and commissioning of IP networks already exist.
5. IP-based devices can be connected readily to other IP-based networks, without the need for intermediate entities like translation gateways or proxies.

6LowPAN Needs Adaptation

Header Size Calculation. . .

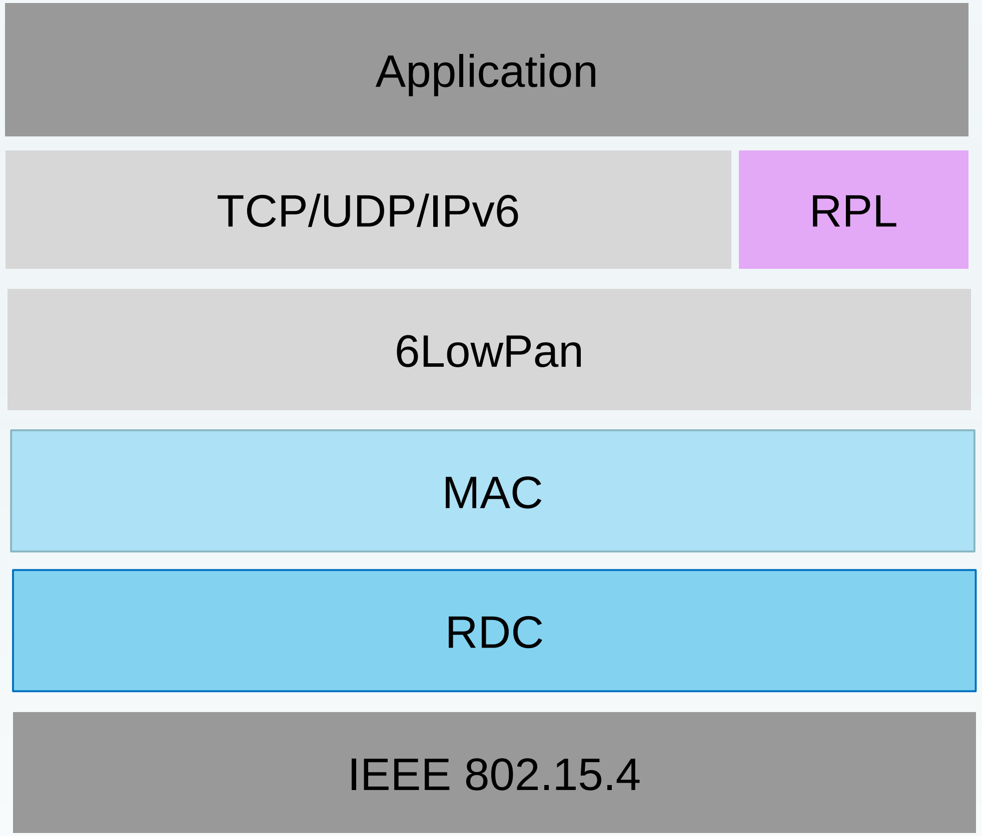
- IPv6 header is 40 octets, UDP header is 8 octets
- 802.15.4 MAC header can be up to 25 octets (null security) or 25+21=46 octets (AES-CCM-128)
- With the 802.15.4 frame size of 127 octets, we have
  - 127-25-40-8 = 54 octets (null security)
  - 127-46-40-8 = 33 octets (AES-CCM-128)

  of space left for application data!

IPv6 MTU Requirements

- IPv6 requires that links support an MTU of 1280 octets
- Link-layer fragmentation / reassembly is needed

6LowPAN Needs Adaptation Between Network and MAC



- 6LowPan layer in the figure is responsible for several functions required for IP networks to work over a PHY/MAC layer with 127 bytes of frame length.
- 6LowPAN does header compression, fragmentation, defragmentation, etc.

6LowPAN OverView

Overview

- The 6LowPAN protocol is an adaptation layer allowing to transport IPv6 packets over 802.15.4 links
- Uses 802.15.4 in unslotted CSMA/CA mode (strongly suggests beacons for link-layer device discovery)
- Based on IEEE standard 802.15.4-2003
- Fragmentation / reassembly of IPv6 packets
- Compression of IPv6 and UDP/ICMP headers
- Mesh routing support (mesh under)
- Low processing / storage costs

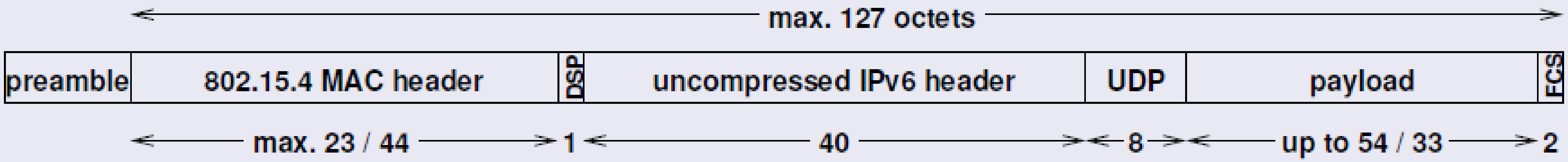
6LowPAN Dispatch Codes

- All LoWPAN encapsulated datagrams are prefixed by an encapsulation header stack.
- Each header in the stack starts with a header type field followed by zero or more header fields.

Bit Pattern	Short Code	Description
00 xxxxxx	NALP	Not A LoWPAN Packet
01 000001	IPv6	uncompressed IPv6 addresses
01 000010	LOWPAN_HC1	HC1 Compressed IPv6 header
01 010000	LOWPAN_BC0	BC0 Broadcast header
01 111111	ESC	Additional Dispatch octet follows
10 xxxxxx	MESH	Mesh routing header
11 000xxx	FRAG1	Fragmentation header (first)
11 100xxx	FRAGN	Fragmentation header (subsequent)

Uncompressed IPv6 Case

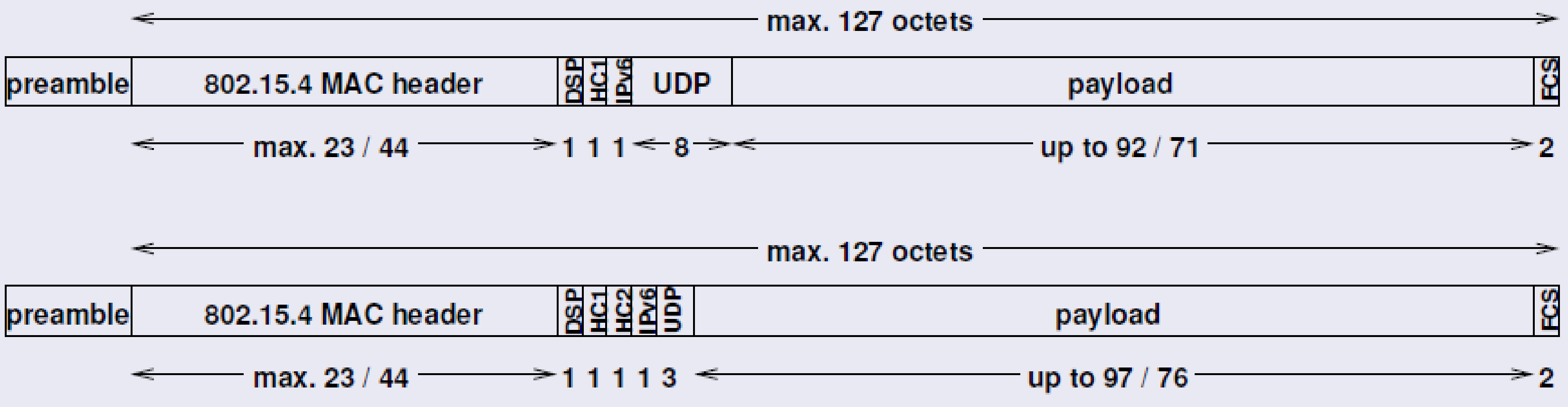
Uncompressed IPv6/UDP (worst case scenario)



- Dispatch code (01000001_2) indicates no compression
- Up to 54 / 33 octets left for payload with a max. size MAC header with null / AES-CCM-128 security
- The relationship of header information to application payload is obviously really bad

Compressed IPv6 Case

Compressed Link-local IPv6/UDP (best case scenario)



- Dispatch code (01000010_2) indicates HC1 compression
- HC1 compression may indicate HC2 compression follows
- This shows the maximum compression achievable for link-local addresses (does not work for global addresses)
- Any non-compressable header fields are carried after the HC1 or HC1/HC2 tags (partial compression)

Header Compression Status

- Compression Principles (RFC 4944)
  - Omit any header fields that can be calculated from the
  - context, send the remaining fields unmodified
  - Nodes do not have to maintain compression state (stateless compression)
  - Support (almost) arbitrary combinations of compressed /uncompressed header fields

- Ongoing Work
  - Compression for globally routable addresses (HC1G)
  - Stateful compression (IPHC, NHC)

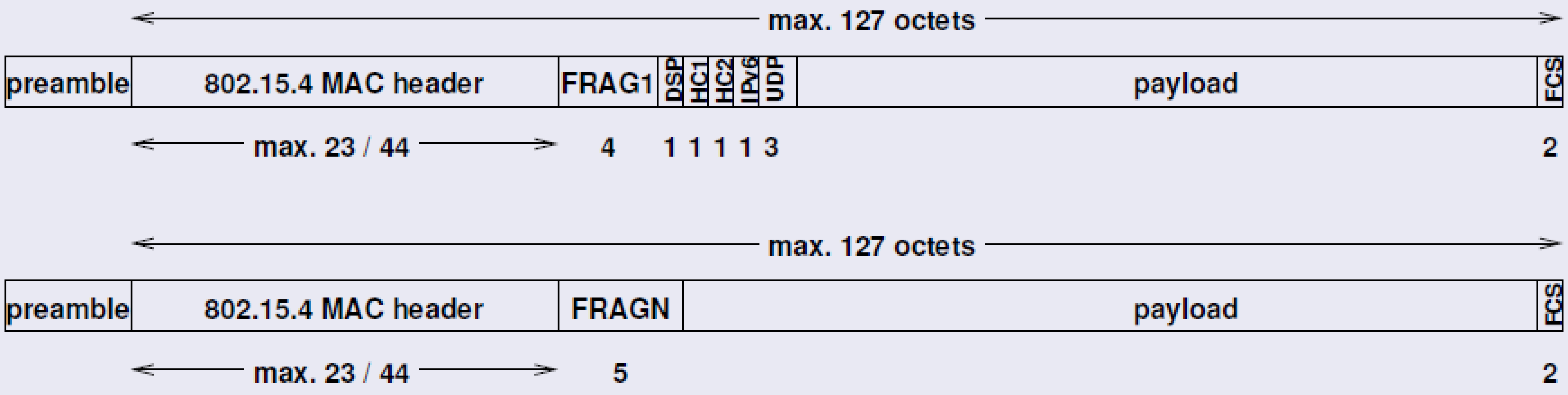
Fragmentation & Reassembly

- Fragmentation Principles (RFC 4944)
  - IPv6 packets to large to fit into a single 802.15.4 frame are fragmented.
  - A first fragment carries a header that includes the datagram size (11 bits) and a datagram tag (16 bits).
  - Subsequent fragments carry a header that includes the datagram size, the datagram tag, and the offset (8 bits).
  - Time limit for reassembly is 60 seconds.

- Ongoing Work
  - Recovery protocol for lost fragments (RFC 4944 requires to resend the whole set of fragments)

An Example

Fragmentation Example (compressed link-local IPv6/UDP)



Homework Question (consult RFC 4944 first)

- How many fragments are created for an 1280 octet IPv6 packet with no / maximum compression and none / AES-CCM-128 link-layer security?

Routing over Low Power Links
IETF RPL

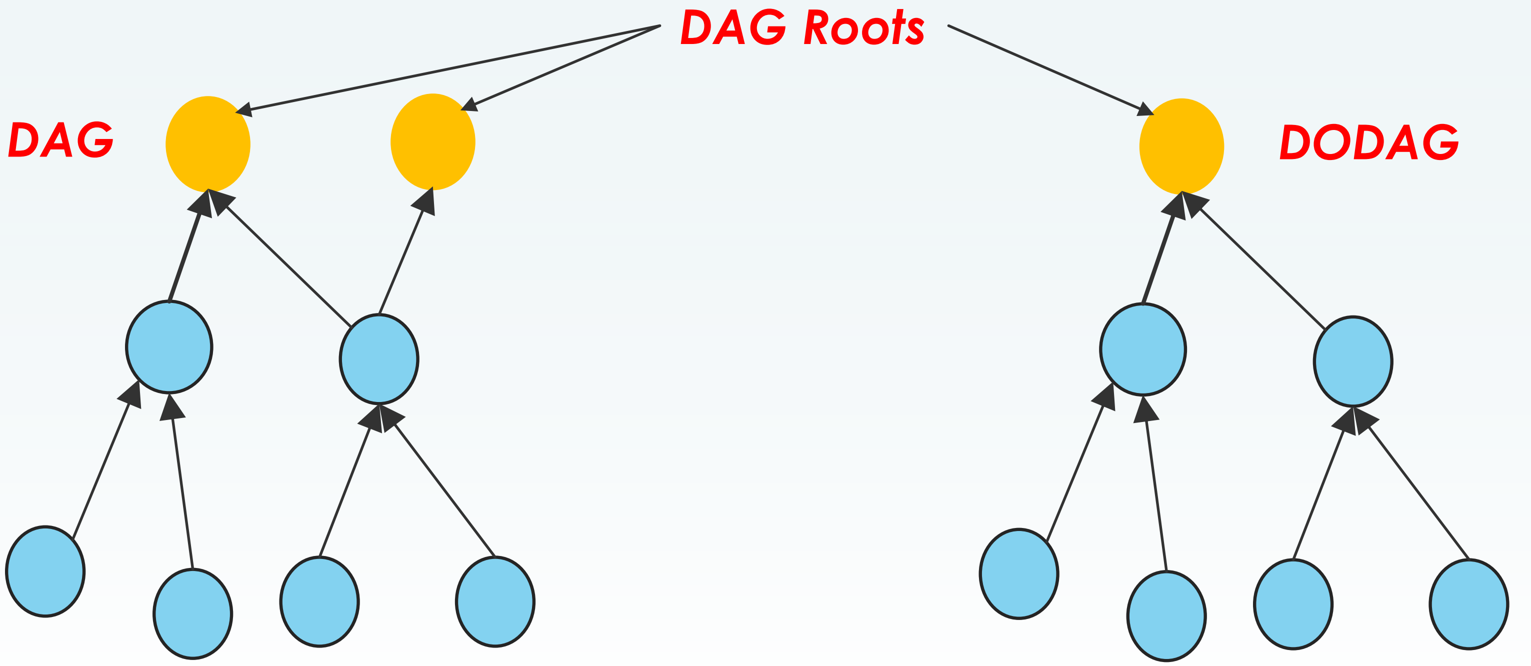
Motivation

- Routing Requirements
  - Urban LLNs [RFC5548]
  - Industrial LLNs [RFC5673]
  - Home Automation LLNs [RFC5826]
  - Building Automation LLNs [RFC5867]

- Common Characteristics
  - Low power and Lossy Networks (LLNs) consisting largely of constrained nodes.
  - Lossy and unstable links, typically supporting low data rates, relatively low packet delivery rates.
  - Traffic patterns are not simply point-to-point, but in many cases point-to-multipoint or multipoint-to-point.
  - Potentially comprising up to thousands of nodes.

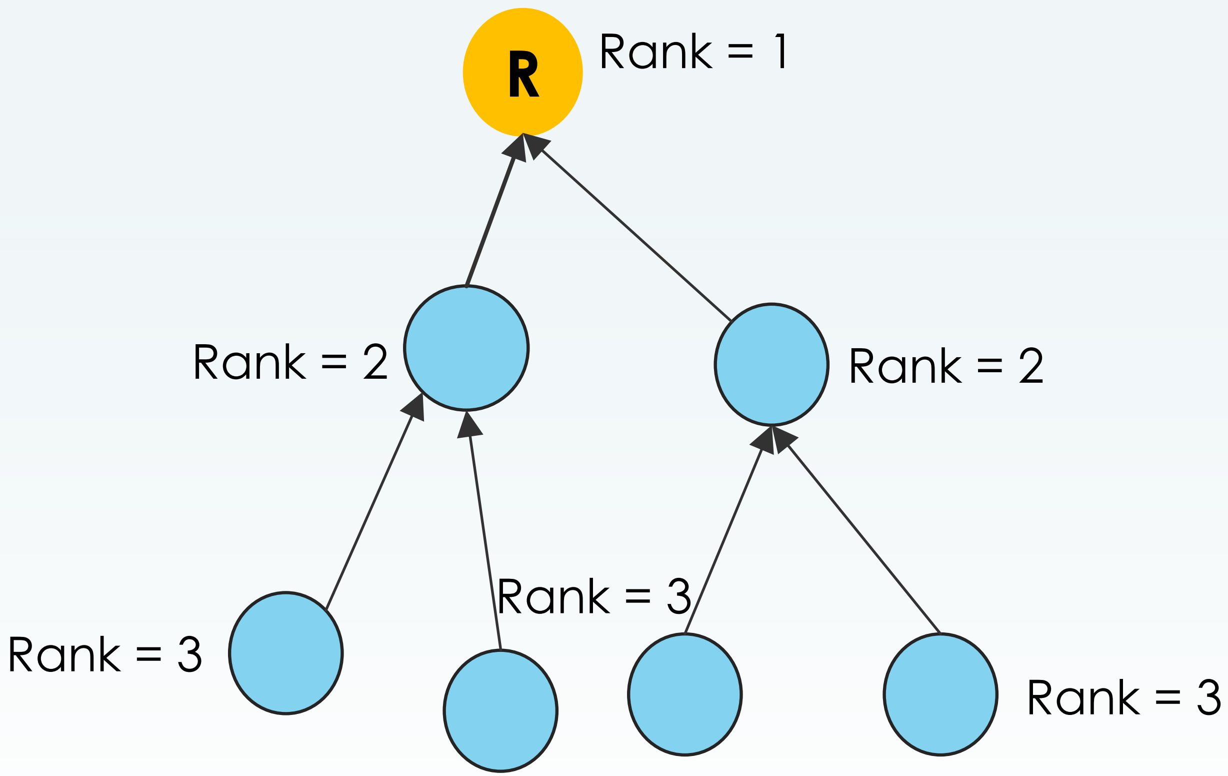
RPL: IPv6 Routing Protocol for LLNs

- Definitions:
  - Directed Acyclic Graph (DAG) - a directed graph with no cycles exist.
  - Destination Oriented DAG (DODAG) - a DAG rooted at a single destination.



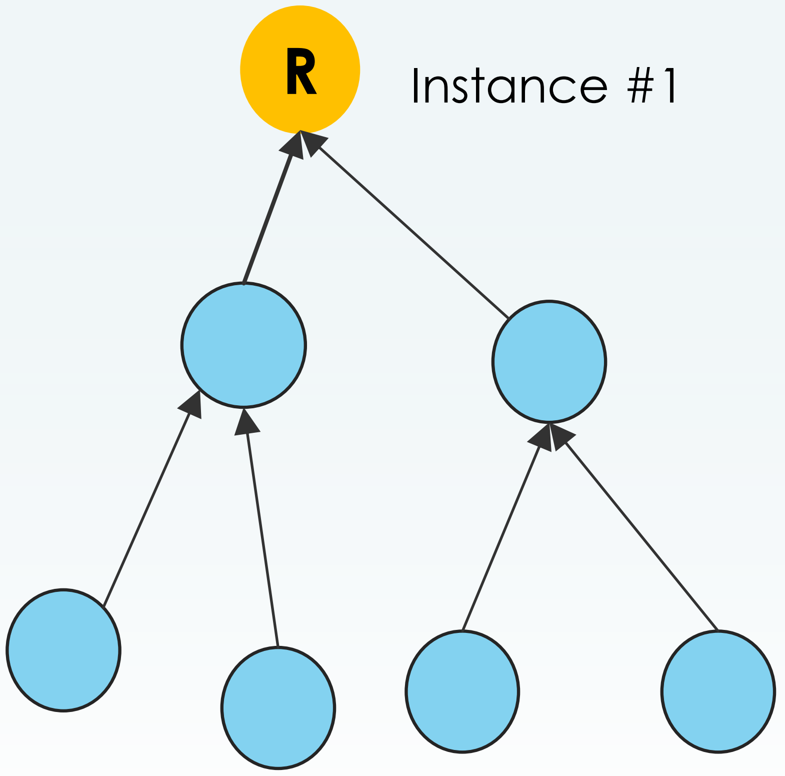
RPL Node Rank

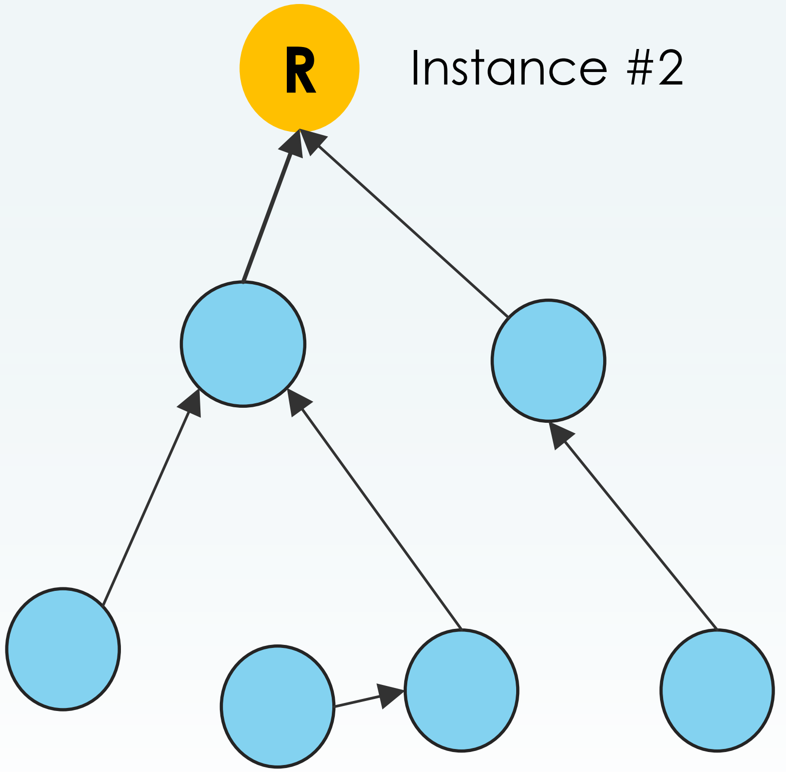
- Denes a node's relative position within a DODAG with respect to the DODAG root.



RPL: IPv6 Routing Protocol for LLNs

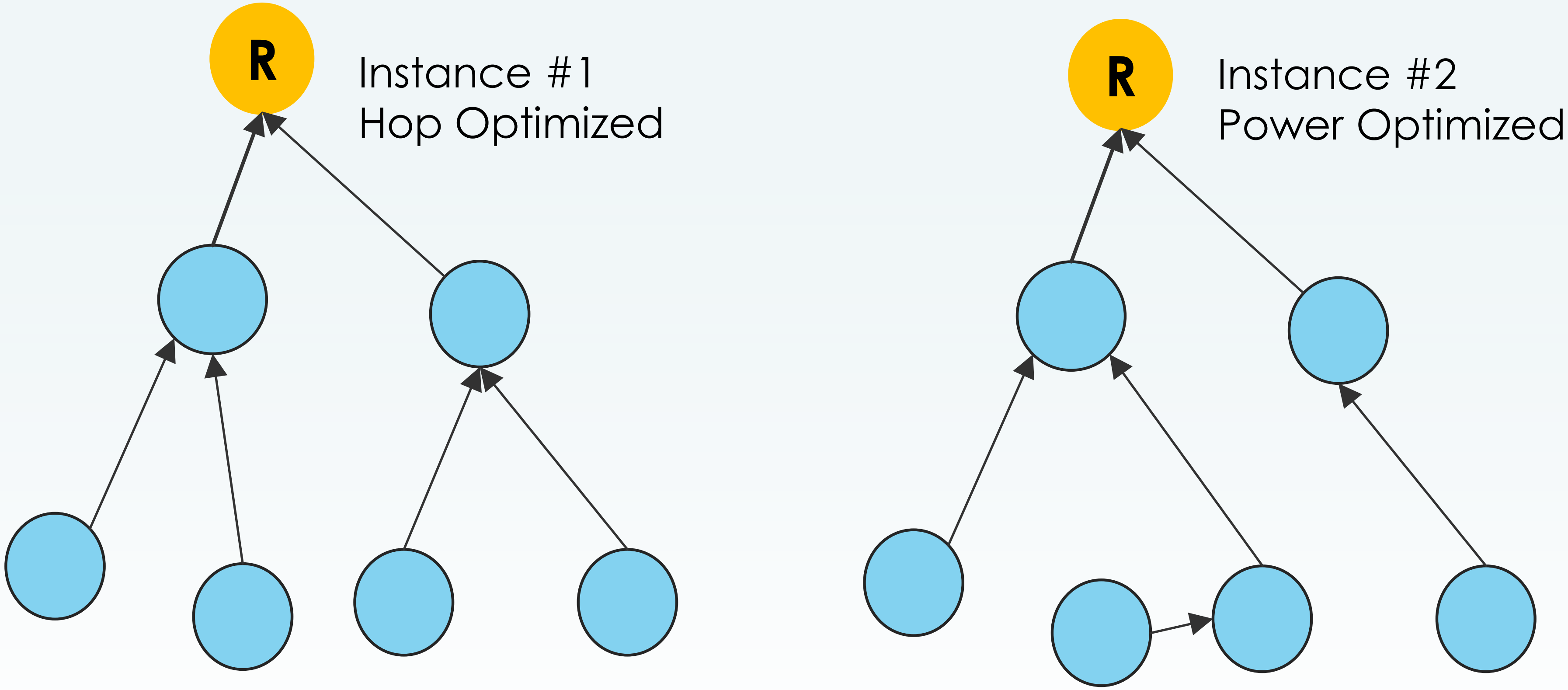
- Assumption: most traffic in LLNs flows through few nodes
  - many-to-one;
  - one-to-many;
  - Not optimised for p2p traffic
- Approach: build a topology (Instance) where routes to these nodes are optimized (DODAG(s) rooted at these nodes)





RPL Instance

- Defines Optimization Objective when forming paths towards roots based on one or more metrics one-to-many;
- Metrics may include both Link properties (Reliability, Latency) and Node properties (Powered or not).
- A network may run multiple instances concurrently with different optimization criteria



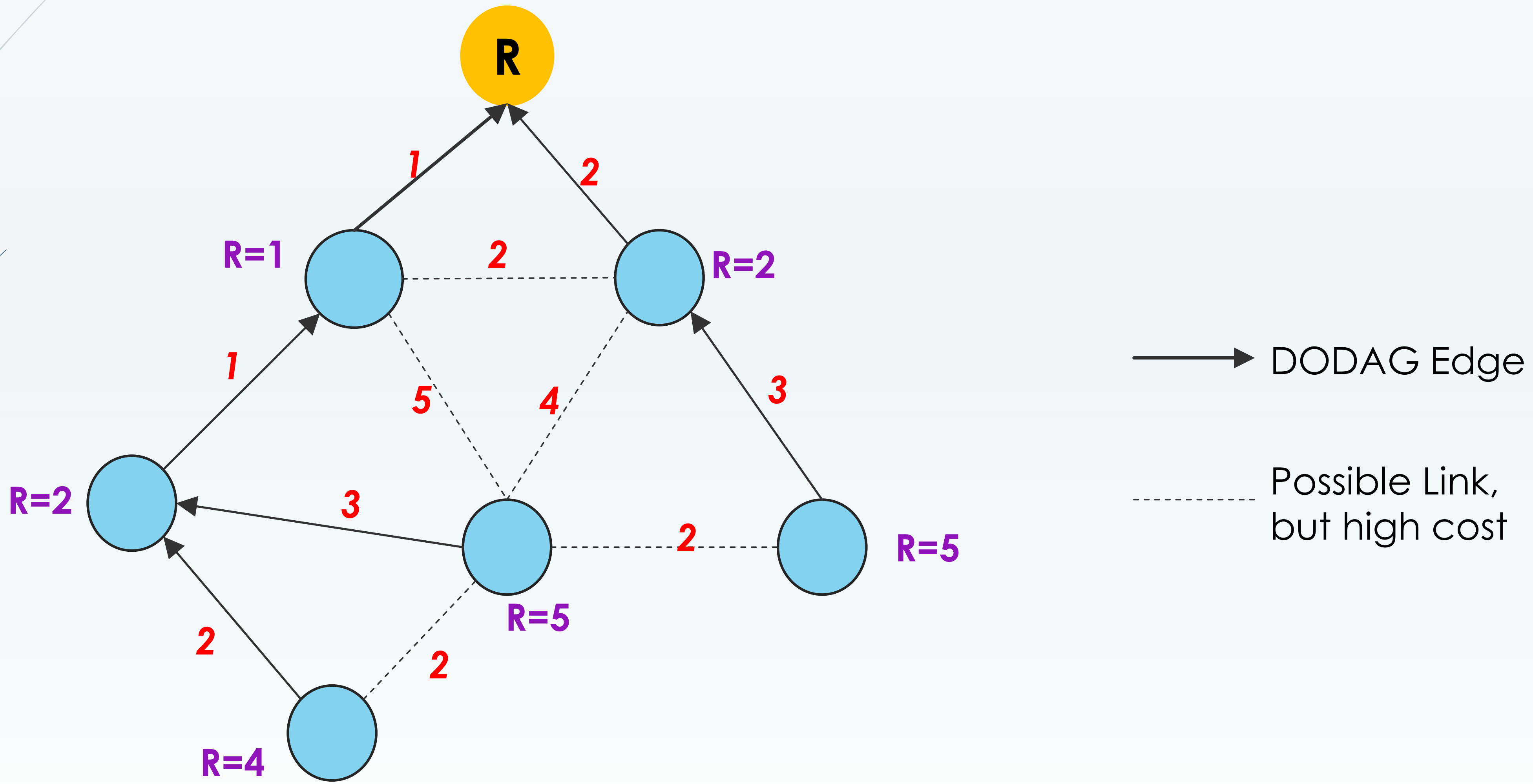
RPL Control Messages

- RPL defines a new ICMPv6 message with three possible types:
  - DAG Information Object (DIO) - carries information that allows a node to discover an RPL Instance, learn its conguration parameters and select DODAG parents.
  - DAG Information Solicitation (DIS) - solicit a DODAG Information Object from a RPL node.
  - Destination Advertisement Object (DAO) - used to propagate destination information upwards along the DODAG.

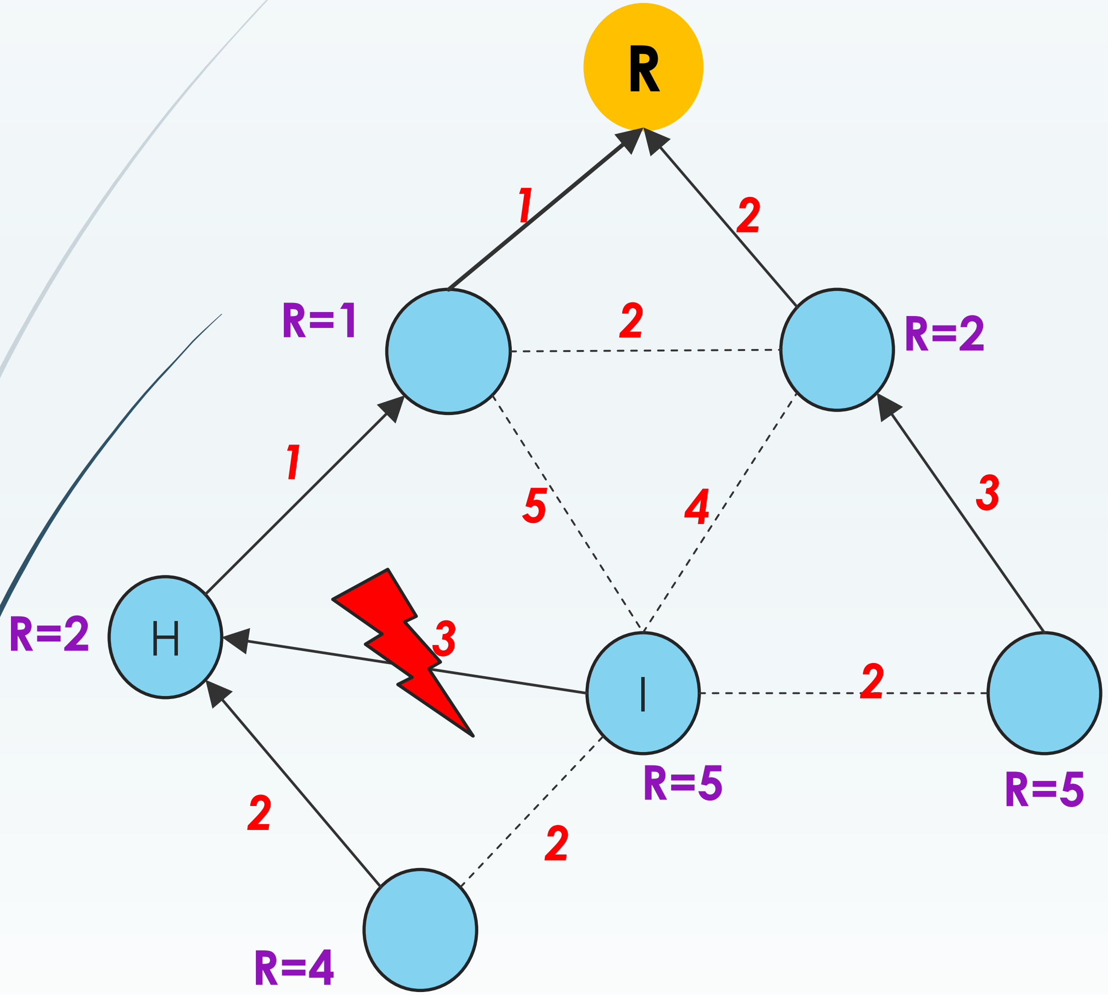
DODAG Construction

- Nodes periodically send link-local multicast DIO messages
- Stability or detection of routing inconsistencies influence the rate of DIO messages.
  - ***No problems: Double DIO period until DIO_PERIOD_MAX***
  - ***Problem detected: Reset DIO period to DIO_PERIOD_MIN***
- Nodes listen for DIOs and use their information to join a new DODAG, or to maintain an existing DODAG
- Nodes may (shall) use a DIS message to solicit a DIO
- Based on information in the DIOs the node chooses parents that minimize path cost to the DODAG root.

DODAG Example

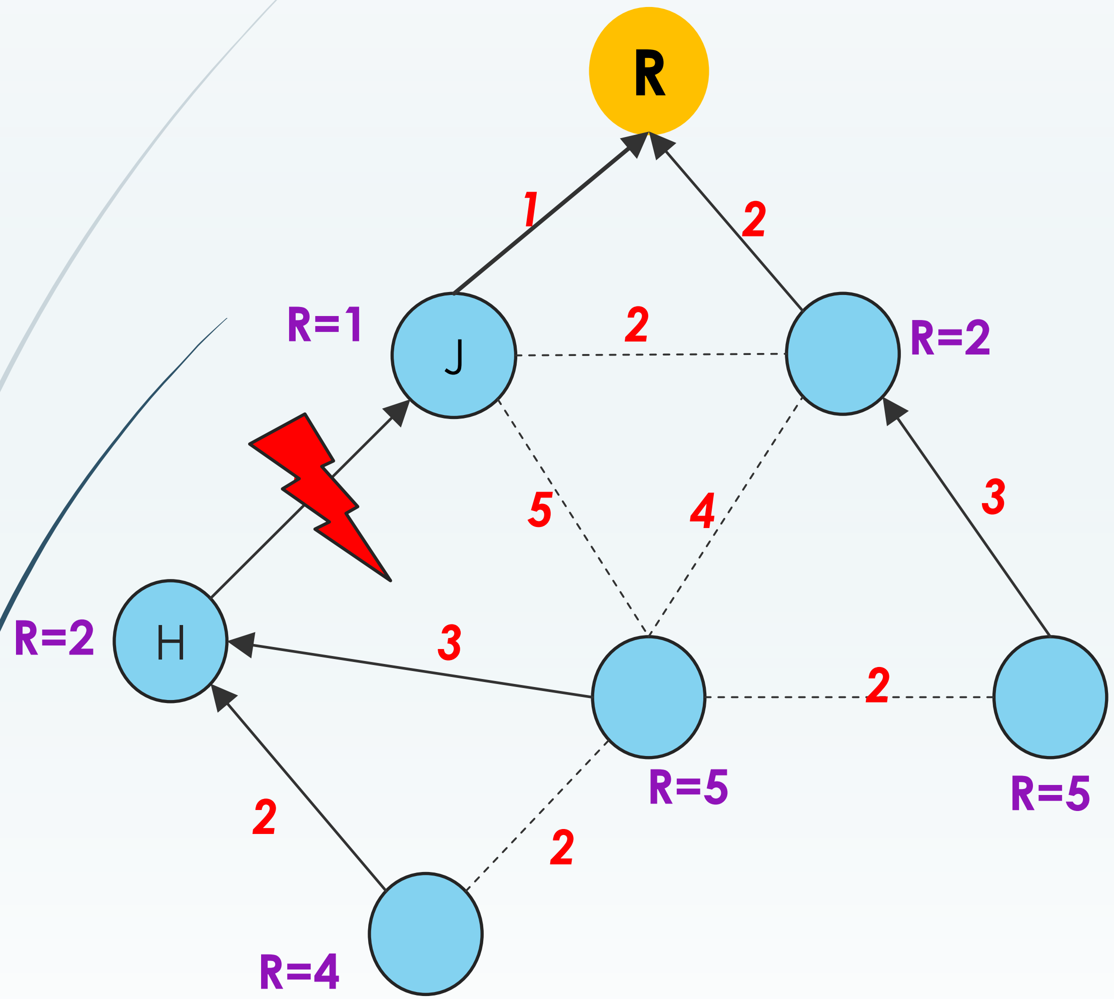


DODAG Repair



- Link between H&I fails:
  - Find an alternative link with minimal rank.
  - Generally speaking, this happens automatically when a link degrades.
  - The failing links rank increases and the node choses a better link from its possible parent set.

DODAG Repair



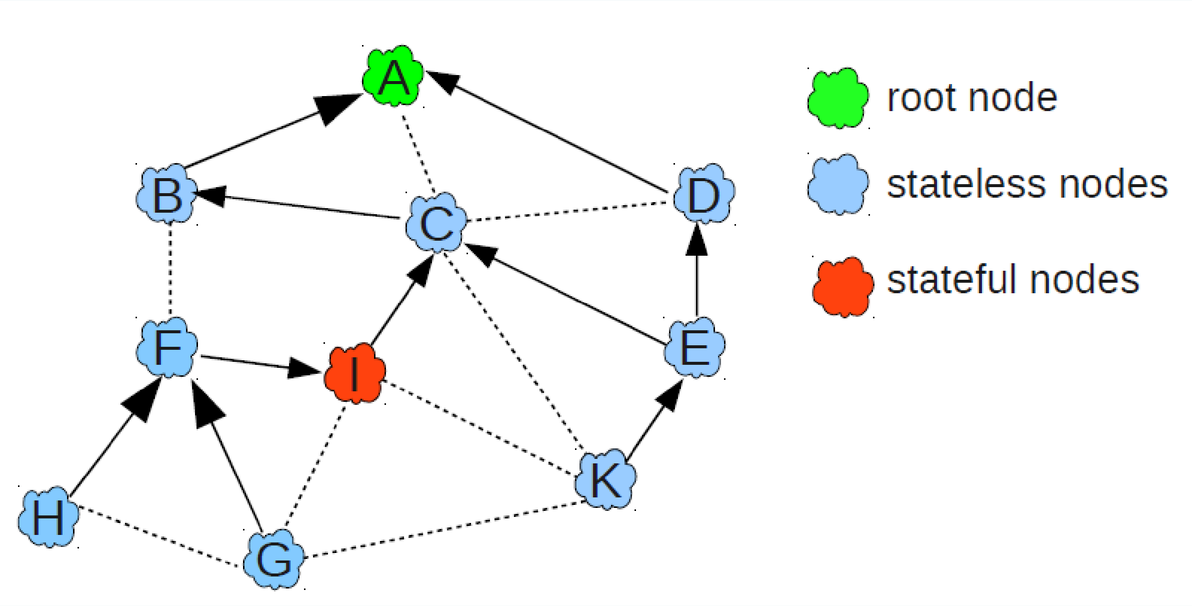
- If there is no alternative parent to choose:
  - 1) Global repair: create a new DODAG with a new sequence number.
  - 2) Local repair: poison the SUB-DODAG by setting your own rank to infinity.

Downward Routes and Destination Advertisement

- Nodes inform parents of their presence and reachability to descendants by sending a DAO message
- ***Node capable of maintaining routing state*** -> Aggregate routes
- ***Node incapable of maintaining routing state*** -> attach a next-hop address to the reverse route stack contained within the DAO message

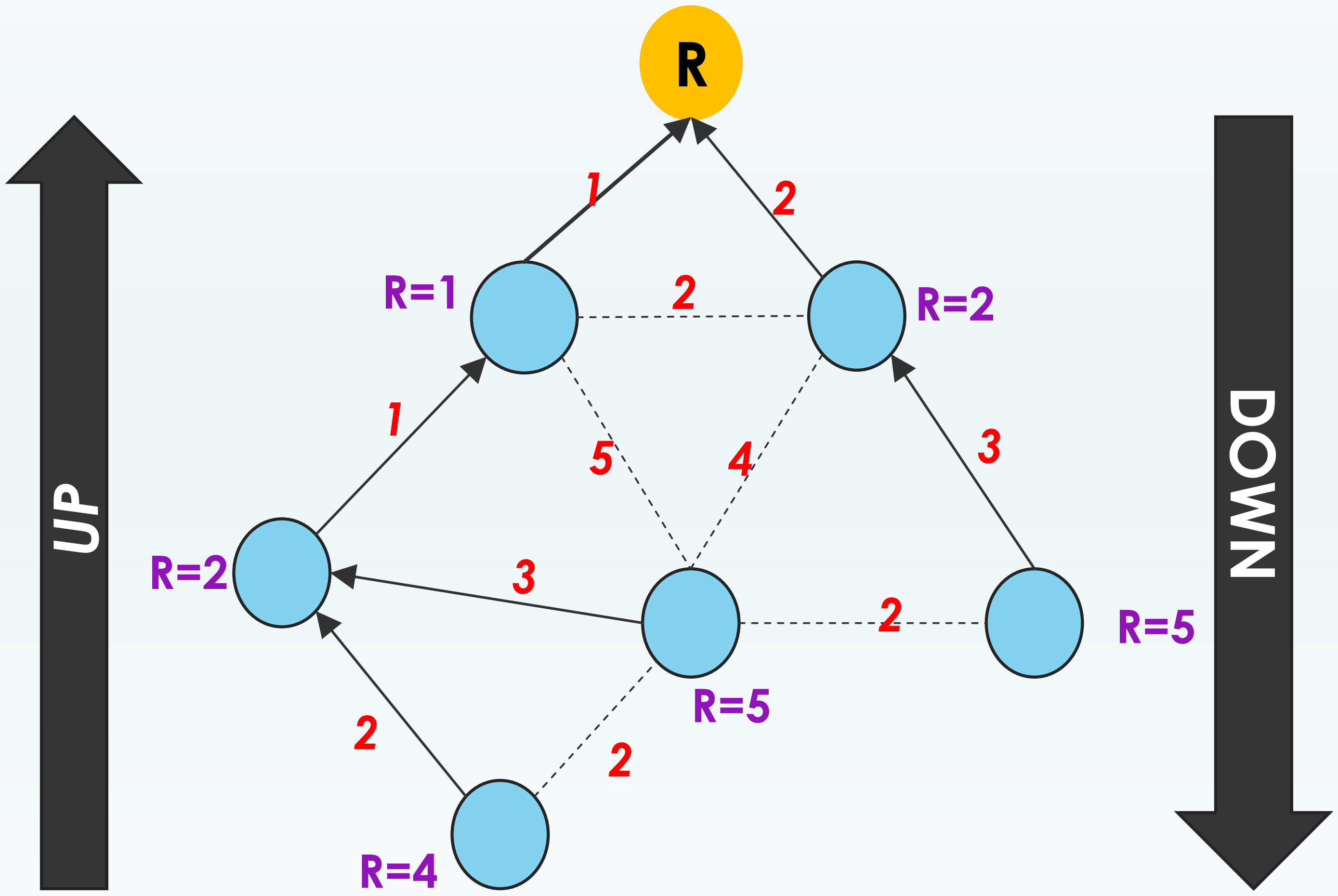
Destination Advertisement - Example

- H sends a DAO message to F indication the availability of H, F adds the next-hop and forwards the message to I
- G sends a DAO message to F indication the availability of G, F adds the next-hop and forwards the message to I
- F sends a DAO message to I indication the availability of F
- I aggregates the routes and sends a DAO advertising (F-I)



RPL Traffic Flows

- Up towards the DAG root for many-to-one
- I Down away from the DAG root for one-to-many
- I Point-to-point via up*down*



RPL Summary

- Optimized for many-to-one and one-to-many traffic patterns
- Routing state is minimized: stateless nodes have to store only instance(s) configuration parameters and a list of parent nodes.
- Takes into account both link and node properties when choosing paths
- Link failures does not trigger global network re-optimization

Thank You for Your Attention.