Internet of Things

Lecture 4 - 6LoWPAN & RPL

6LoWPAN

Network Protocols

IPv4	IPv6	6LoWPAN
• Exhausted in 2011 • 32-bit address	• 128-bit addresses • Fit for large IoT networks • Not enough resources on low power devices	• Adaptation layer • Header compression • Fragmentation

6LoWPAN Standard

- Internet Engineering Task Force (IETF)
  - TCP, UDP, HTTP, CoAP, etc.
- RFC 4944 - first 6LoWPAN standard
- RFC 6282 - header compression
- RFC 6775 - neighbor discovery
- Over IEEE 802.15.4
- Adapted to work with other low-power technologies
  - Bluetooth Smart
  - Wi-Fi low-power

Network Architecture

- 6LoWPAN mesh network
- Edge router (6LBR)
  - Generates & manages 6LoWPAN network
  - Transfers between 6LoWPAN nodes and the Internet
  - Transfers between 6LowPAN nodes
  - Network level
- Routers (6LR)
  - Routes traffic from one node to another
- Hosts (6LN)
  - Do not route traffic
  - Low power nodes

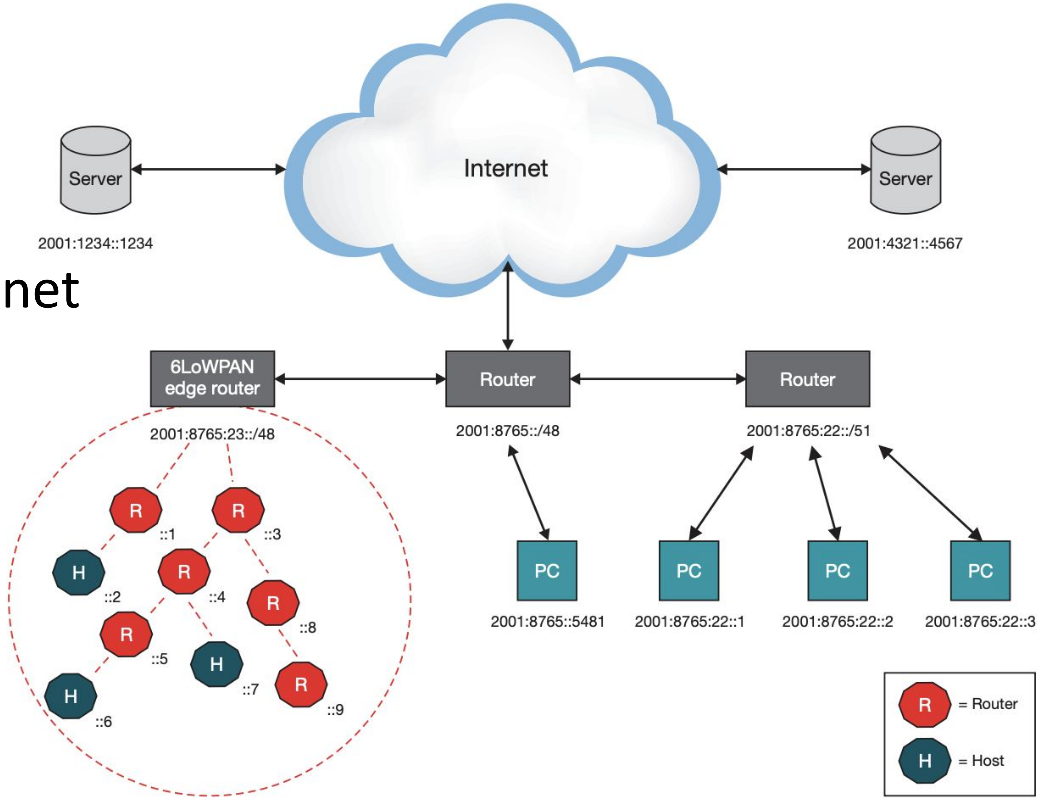


Figure 1. An example of an IPv6 network with a 6LoWPAN mesh network

Source: Olsson, Jonas. "6LoWPAN demystified." Texas Instruments 13 (2014).

Networking Stack

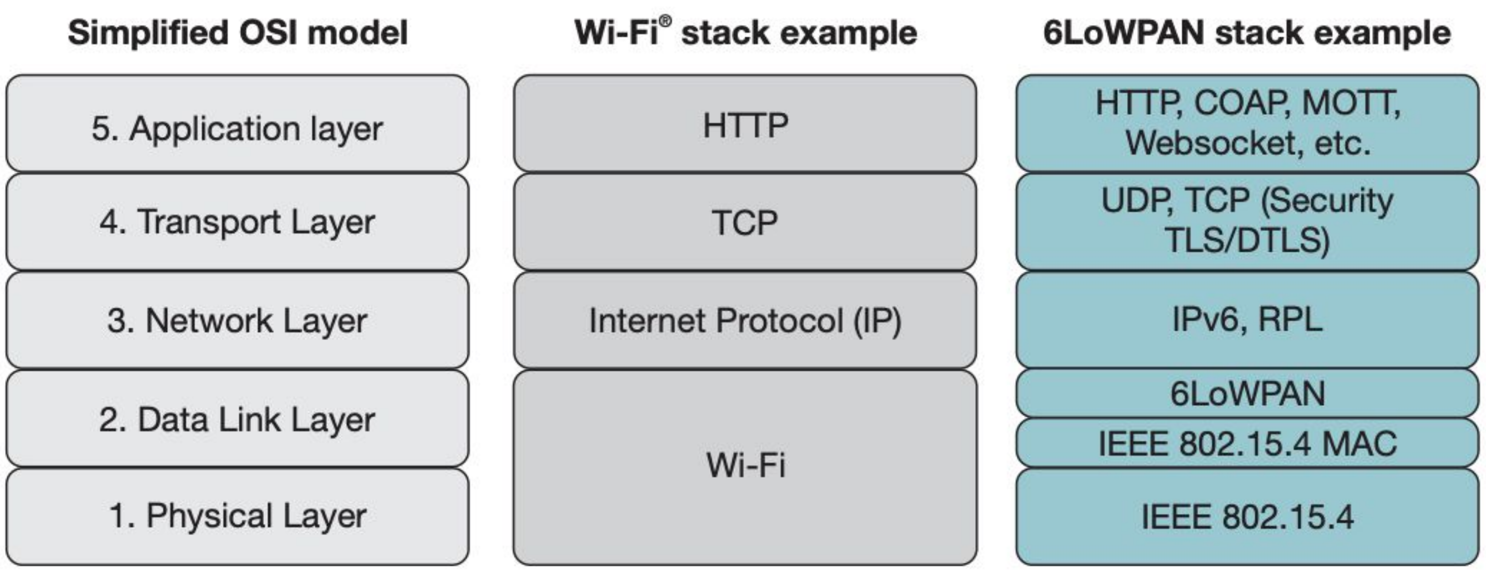


Figure 2. The OSI model, a Wi-Fi® stack example and the 6LoWPAN stack

Image source: Olsson, Jonas. "6LoWPAN demystified." Texas Instruments 13 (2014).

IPv6 over IEEE 802.15.4

- IPv6
  - MTU is 1280 bytes
  - Reflects technology advancement
- 802.15.4
  - Low power, low cost devices
  - Frame size is 127 bytes
  - Maximum bandwidth 250 Kbps
  - MAC addresses on 64 bits or 16 bits
  - Minimize header overhead & memory consumption

IPv6 over IEEE 802.15.4

- Main challenges for using IPv6 over 802.15.4
- IPv6 has minimum MTU 10 times larger
  - IPv6 - 40 bytes headers, TCP - 20 bytes, UDP - 8 bytes
  - Solution: Fragmentation & header compression
- Low power and lossy networks
  - Interferences, unstable links, packet loss
  - Solution: Adaptive and responsive network layer

IETF - RFC 6282

- 6LoWPAN Working Group from IETF => RFC 6282
  - Encapsulation of IPv6 packet into 802.15.4 frame
- Header compression
  - Stateless or context-based compression
  - The elimination of header fields that can be derived from other headers
  - Same network prefix
  - Determine IPv6 addresses and field sizes

IETF - RFC 6282

- Fragmentation
  - Fragment data to fit in 802.15.4 frames
- Stateless auto-configuration
  - 6LoWPAN nodes generate their own addresses
  - Duplicate address detection (DAD)

Header Compression

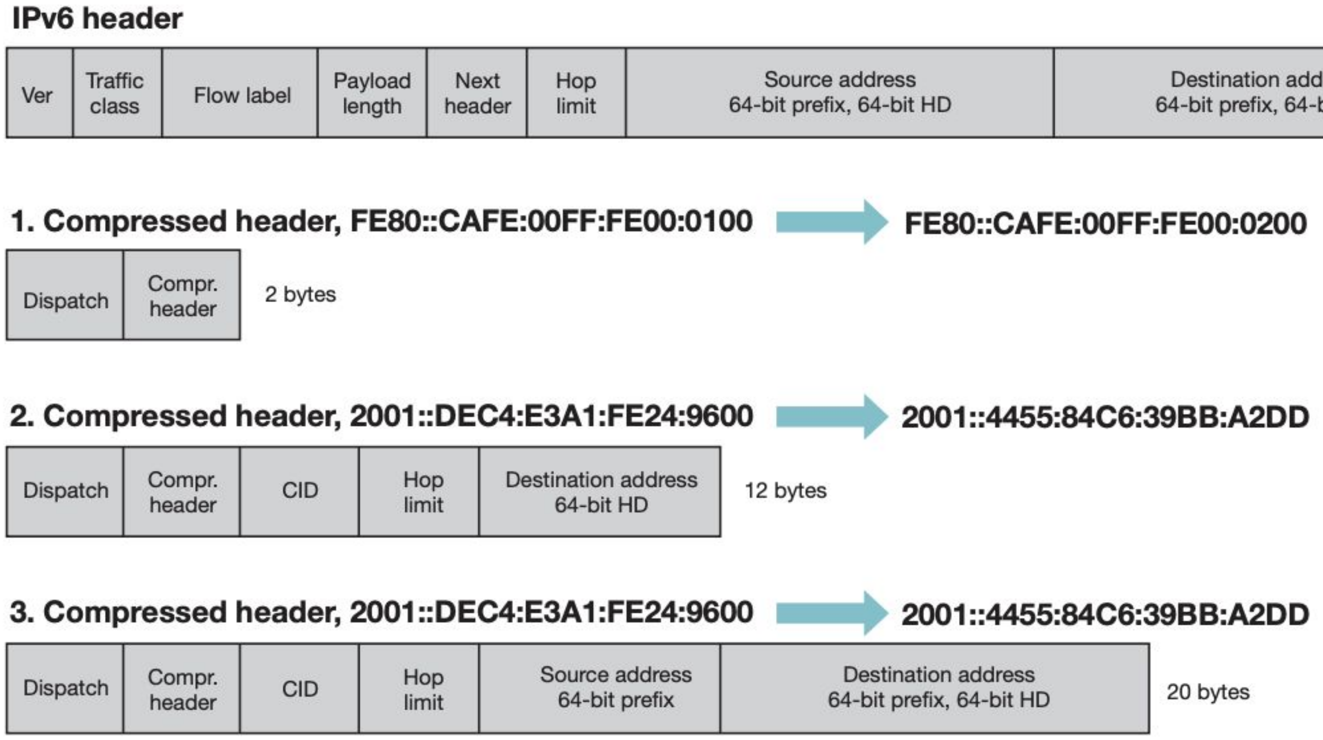


Figure 3. 6LoWPAN IPv6 header compression examples

Image source: Olsson, Jonas. "6LoWPAN demystified." Texas Instruments 13 (2014).

- Stateless & shared-context compression
- IPv6 addr = network prefix + interface ID
- Interface ID - derived from MAC address

1. between nodes from the local network
   - exclude both link-local addresses
   - useful for routing protocols
2. destination is external but prefix is known
   - exclude src addr & dest prefix
3. destination is external and prefix is not known
   - exclude interface ID

Fragmentation

- Packets are divided into smaller segments
- Additional information in the headers for the reassembly
- **mesh-under** routing:
  - packets are reassembled at the destination
  - quick routing of fragments, reduced delay
  - if a single fragment is lost the whole packet must be retransmitted
- **route-over** routing:
  - packet is reconstructed at each hop
  - hops are devices with more resources
- Avoid fragmentation - reduced payload + header compression

Stacked headers

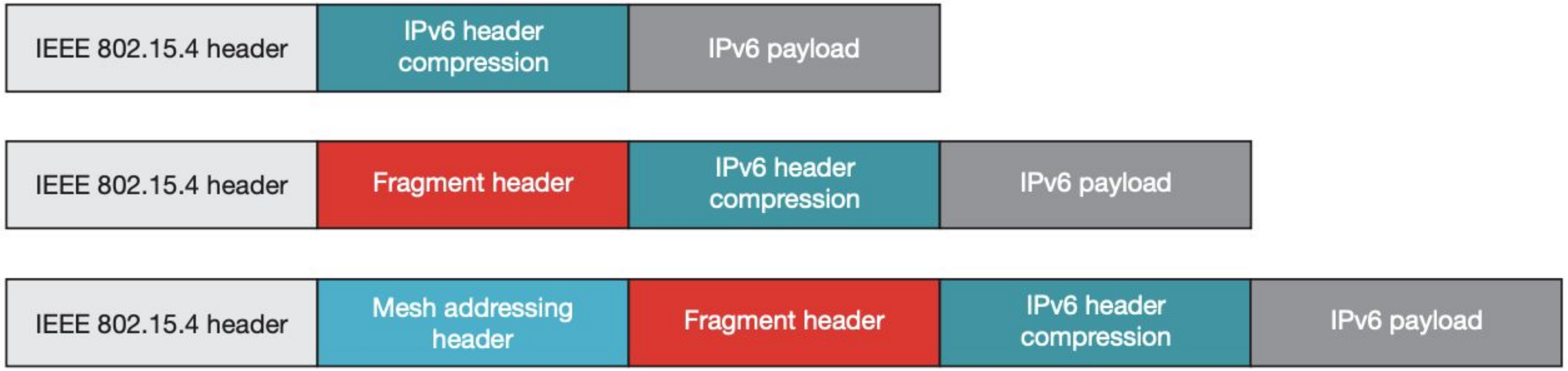


Figure 4. 6LoWPAN stacked headers

Image source: Olsson, Jonas. "6LoWPAN demystified." Texas Instruments 13 (2014).

3 types of sub-headers:

- mesh addressing
  - multi-hop topology
  - forward packets
- fragmentation
  - identify fragments
- header compression

Stacked headers

- Fragment header
  - IPv6 packet is bigger than 802.15.4 frame
  - Fragmentation is needed
  - 3 fields:
    - datagram size
      - whole payload size
    - datagram tag
      - identify a set of fragments of the same payload
    - datagram offset
      - location of fragment in payload

Stacked headers

- Mesh addressing header
  - Used in multi-hop topologies for routing
  - 3 fields:
    - hop limit
      - decremented at each hop
      - drop packet when hop limit reaches 0
    - source address
    - destination address
      - 802.15.4 MAC addresses
      - 16 or 64 bits

Routing

- Mesh-under
  - Uses 802.15.4 MAC addresses to forward packets
  - Forwarding is done at link layer
  - IP subnet
  - A single broadcast domain
  - Router IP = edge router
  - All messages are sent to all nodes
  - Fit for small networks

Routing

- Route-over
  - Works at network layer
  - Each node is an IP router
  - Each node implements all functionality (including DAD)
  - Recommended for large networks
  - RPL is a route-over protocol

Routing

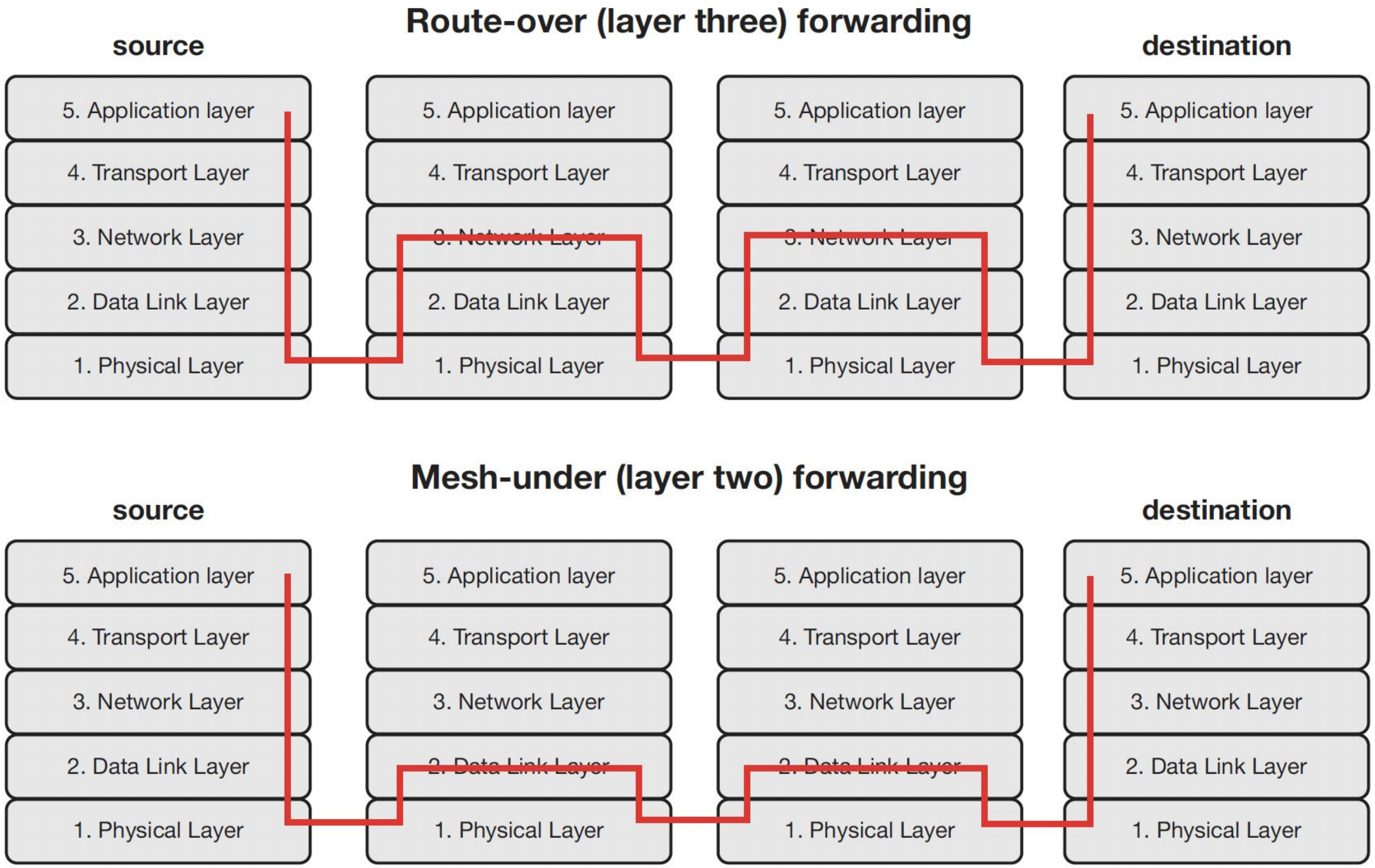


Figure 5. Mesh-under and route-over packet forwarding

Neighbor Discovery

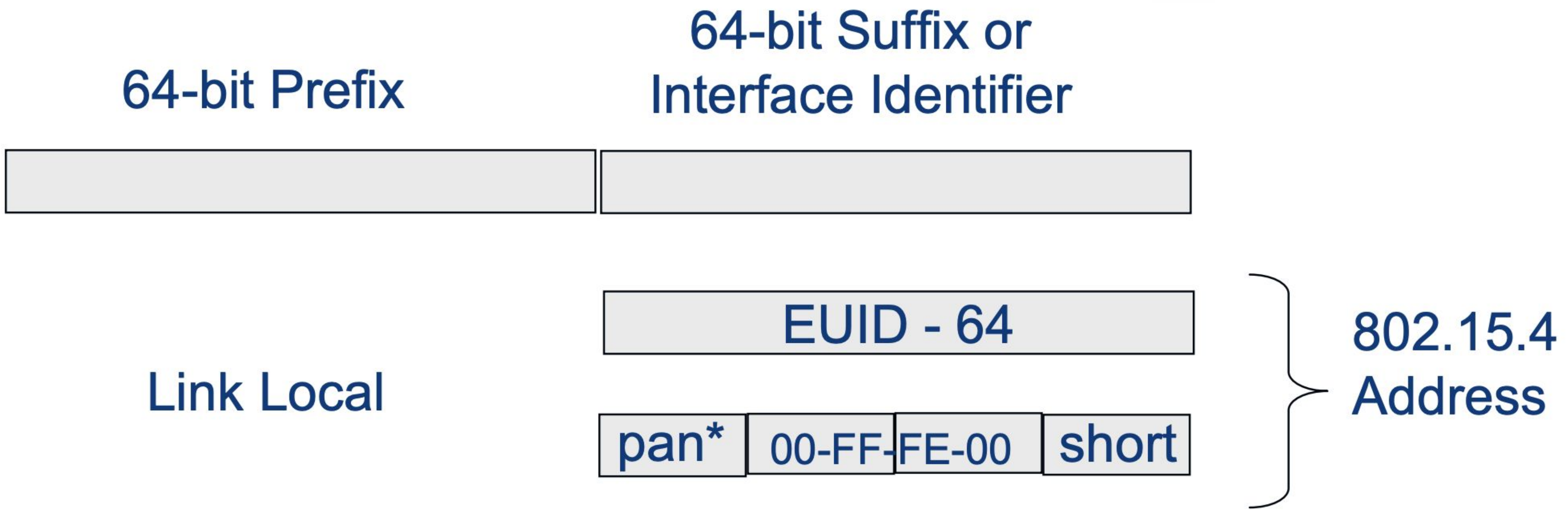
- Neighbor Discovery Protocol (NDP)
  - used for discovering neighbor devices
  - maintain information about available devices
  - configure default routes
  - propagate configuration parameters
- 4 types of messages:
  - Router solicitation (RS)
  - Router advertisement (RA)
  - Neighbor solicitation (NS)
  - Neighbor advertisement (NA)

Neighbor Discovery

- RS/RA
  - discover routers
  - find network prefix
- NS/NA
  - find duplicate addresses (DAD)
  - node generates link-local address and sends NS for verification
  - if it receives NA with duplicate flag, the address is not unique
  - finding neighbours
- Using these 4 messages a node can generate a unique address

Link-local address

- Auto-generate IPv6 address, no need for DHCP
- Link-local address derived from 802.15.4 address (64 or 16 bits)
- Link-local prefix is FE80::/64



Advantages of auto-configuration

- Mesh-under routing
  - local-link address is sufficient to communicate within the local 6LoWPAN network
  - cannot be used for communicating outside the local network
- Router-over routing
  - local-link address for communicating with direct neighbors
  - for multi-hop communication it needs routable address
- Advantage of deriving the IPv6 address from 802.15.4 MAC address
  - eliminate some fields to compress headers
- Same prefix in the network
  - also good for header compression
  - prefix is discovered through RS/RA messages

RPL

RPL

- RPL = Routing Protocol for Low power and lossy networks
- Defined by IETF in RFC 6550
- IETF ROLL working group
- IP smart object networks / Low-power and lossy networks
- “route-over” protocol for 6LoWPAN networks
- Distance-vector & source routing protocol
- Communication:
  - multipoint-to-point
  - point-to-multipoint
  - point-to-point

Topology

- Directed Acyclic Graph (DAG)
  - similar to a tree
  - a node can associate to multiple parents
- Destination-Oriented DAGs (DODAGs),
  - Sink node/gateway - root of the DAG
- RPL instance = one or more DODAGs
  - *RPLInstanceID* identifies the instance
  - An RPL network may have multiple instances
  - A node may belong to several instances, but only to one DODAG in each instance

RPL Topology Example

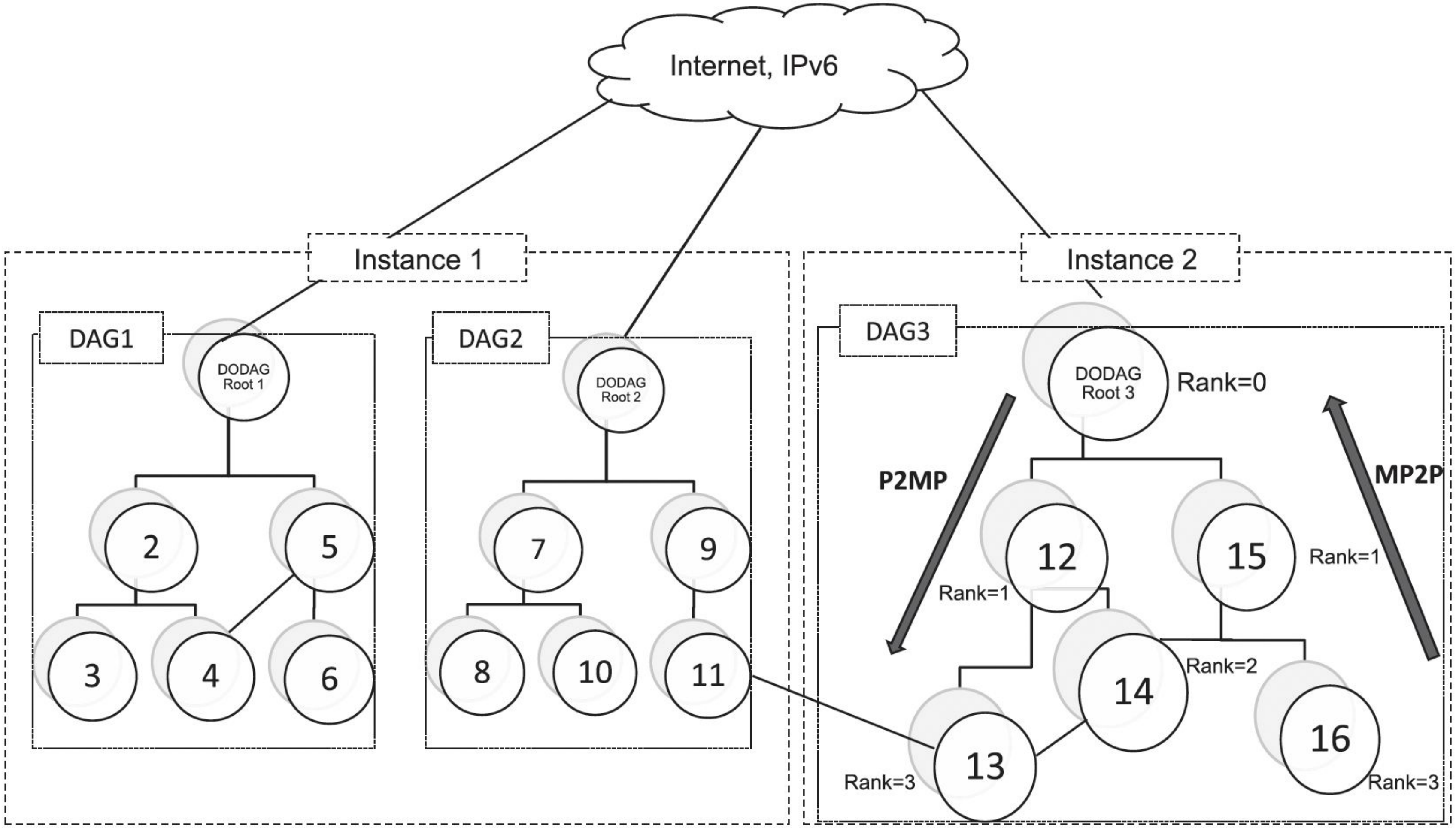


Fig. 1. A RPL network with three DODAGs in two instances.

Image source: Gaddour, Olfa, and Anis Koubâa. "RPL in a nutshell: A survey." Computer Networks 56.14 (2012): 3163-3178.

Topology

- Combines both hierarchical and mesh topologies
- By default it’s a hierarchical topology
  - child-parent relationship
  - sending packets to the preferred parent
- Allows routing through siblings or children
  - when the parent is not available
- Flexibility

Features

- Auto-configuration
  - Compatible with 6LoWPAN
  - Neighbor Discovery
  - Build paths to certain destinations
- Self-healing
  - Nodes may become unavailable
  - Choose more than one parent for redundancy
  - Network adapts to changes

Features

- Loop avoidance & detection
  - DAG is acyclic
  - a node has a higher rank than its parents
  - detects loops and fixes the network
- Independence from link layer protocols
  - runs over multiple link-layer technologies
- Multiple edge routers
  - Multiple DODAGs
  - Each DAG root is an edge router

Network Model

- 3 types of nodes:
  - LBR (Low Power and Lossy Border Router)
    - DODAG root
    - create DAG
    - gateway / edge router
  - Router
    - route packets
    - generate data packets
    - attach to existing DAG
  - Host
    - generate data packets

Network Model

- Every node has a **rank**
  - integer value
  - position relative to other nodes
  - increases in downstream direction
  - used to detect and avoid loops
- Node can be associated with parent or sibling
  - Rank is used to differentiate between parent & sibling
  - List of potential parents and siblings in case the current parent fails
  - A single parent will be the preferred one (based on a metric)

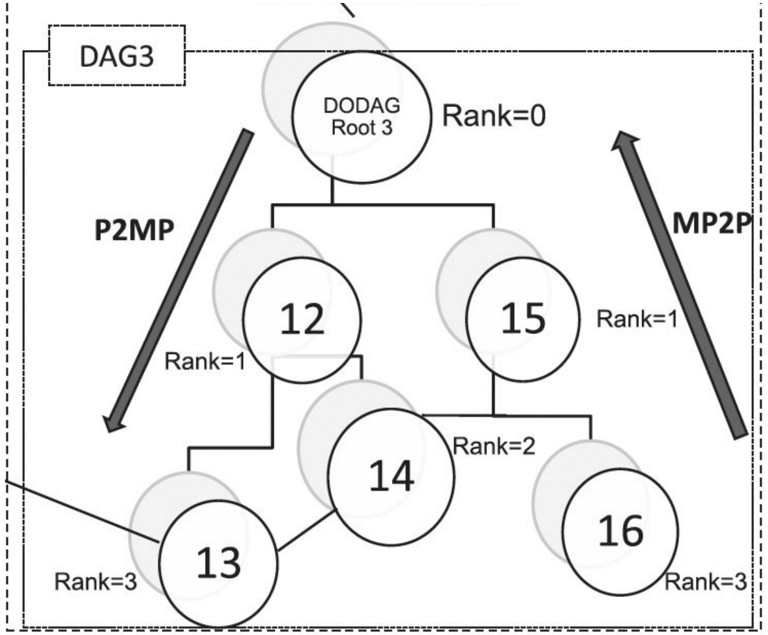


Image source: Gaddour, Olfa, and Anis Koubâa. "RPL in a nutshell: A survey." Computer Networks 56.14 (2012): 3163-3178.

DODAG Construction

- Creating a DODAG is based on 2 operations:
  - broadcast **DIO** control messages
    - sent initially by the root
    - each node computes rank
    - adds parents to list
    - forwards DIO
    - upward routes
  - unicast **DAO** control messages
    - generated by nodes
    - set to preferred parent
    - downward routes

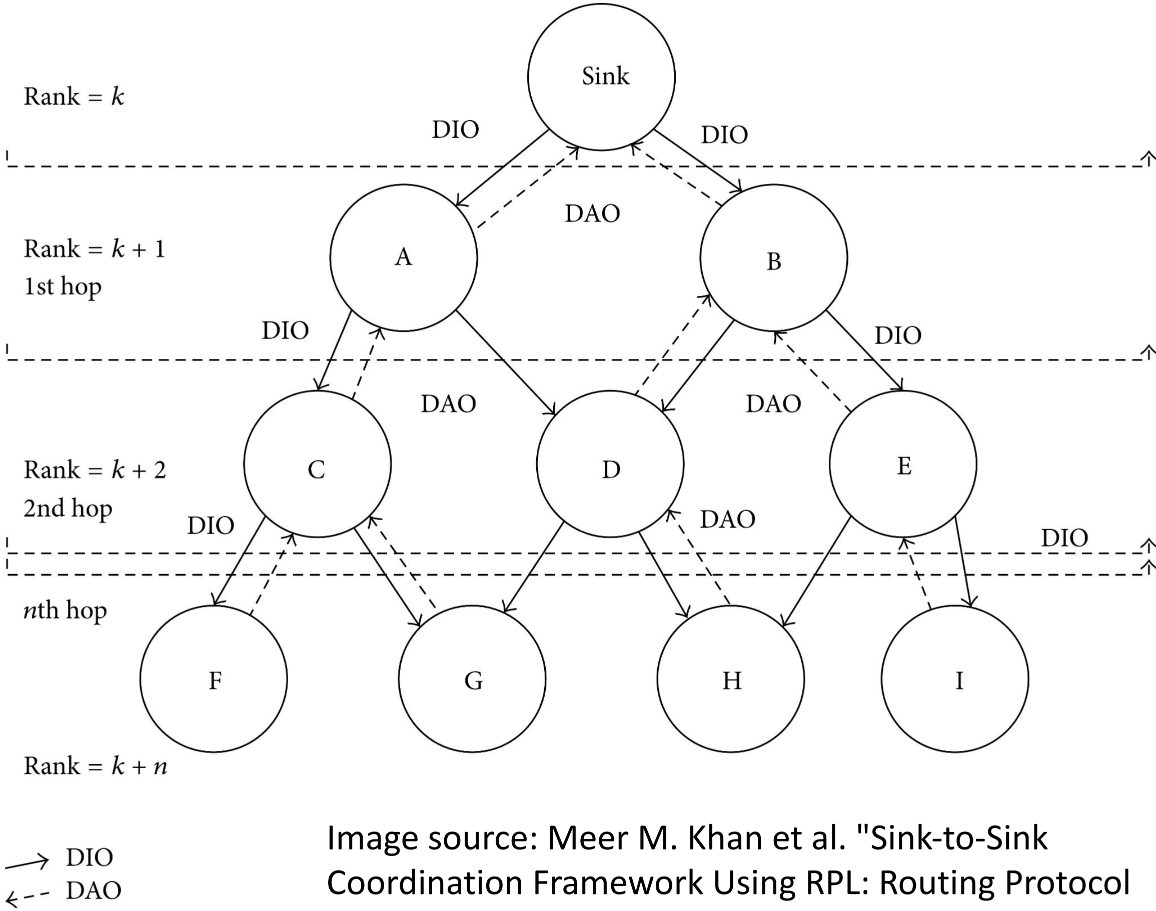


Image source: Meer M. Khan et al. "Sink-to-Sink Coordination Framework Using RPL: Routing Protocol for Low Power and Lossy Networks", Journal of Sensors, vol. 2016, Article ID 2635429, 11 pages, 2016

DODAG Construction

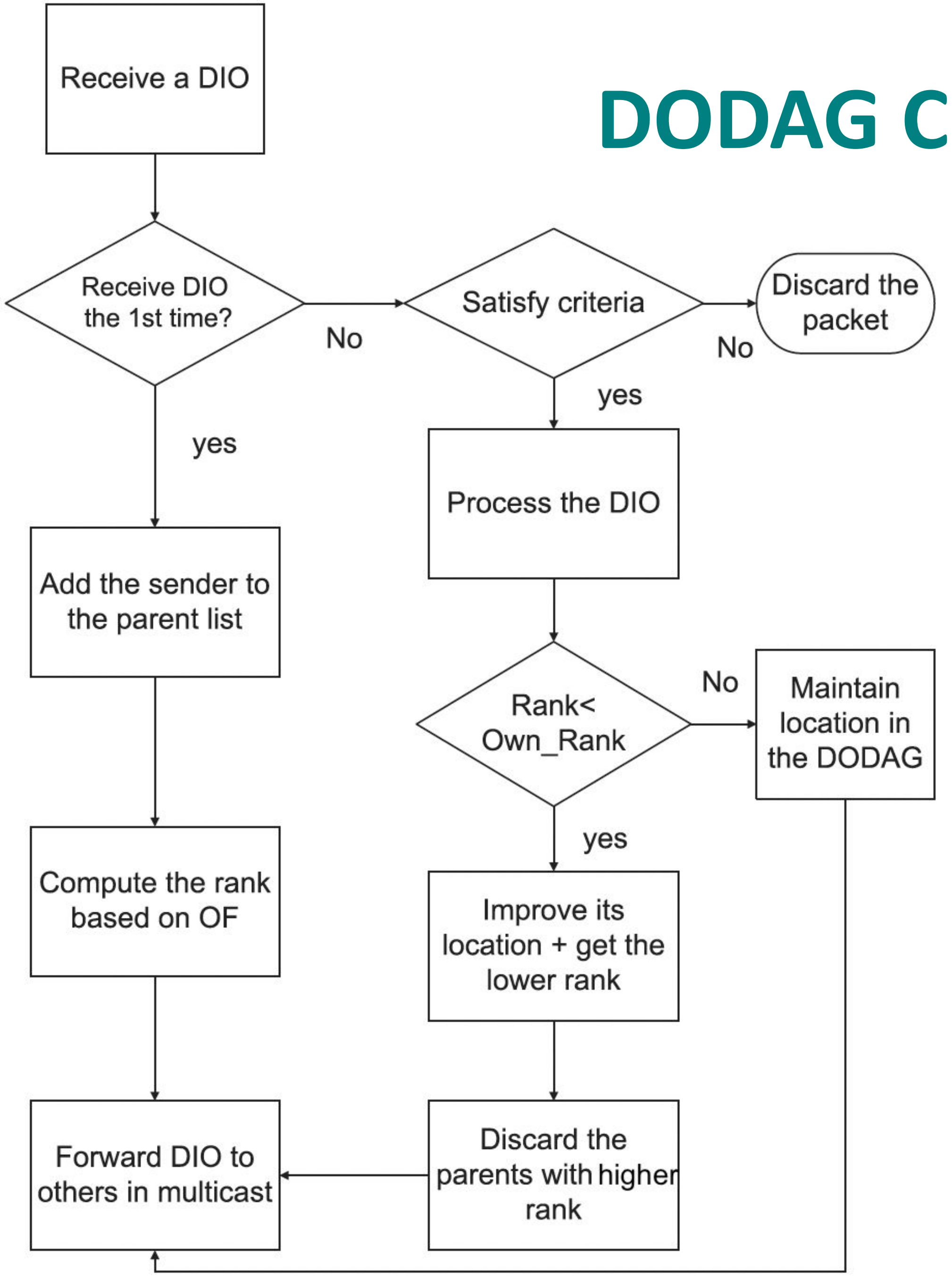


Fig. 5. The operation of a router in a DODAG.

- DIO broadcast (DODAG ID, rank, objective function)
- Node receives first DIO
  - Adds sender to parent list
  - Computes its rank based on OF
  - Forwards the message with updated rank
  - Chooses default parent (default route)
- Node receives another DIO
  - Computes rank
  - If rank is lower, update rank
  - Discard parents with higher rank

Image source: Gaddour, Olfa, and Anis Koubâa. "RPL in a nutshell: A survey." Computer Networks 56.14 (2012): 3163-3178.

Modes of Operation

- DIO messages contain a mode of operation flag
- Mode of operation is different than zero
  - downward routes must be obtained
  - each node sends a DAO to parent
  - each parent adds its address and forwards DAO to its parent
  - until it reaches the root
  - full route between the root and each node

Modes of Operation

- Two modes to build downward routes: storing & non-storing
- Storing mode:
  - Parents aggregate DAO messages from all children then forwards to parent
  - Maintains a routing table & a neighbour table
  - Routing table includes routes to certain destinations
  - Neighbour table includes direct neighbours
  - Needs more storing space

Modes of Operation

- Non-storing mode:
  - Parents add their addresses and forward DAO without storing the message
  - Only the root maintains a routing table
  - Source-routing
    - Packet includes the complete route (hops) to destination
    - A packet sent from one node to another goes through the root

Bibliography

- RFC 4944: https://datatracker.ietf.org/doc/html/rfc4944
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Keywords

- IPv6
- 6LoWPAN
- Header compression
- Fragmentation
- Routing
- RPL
- DODAG
- Neighbor discovery
- Auto-configuration