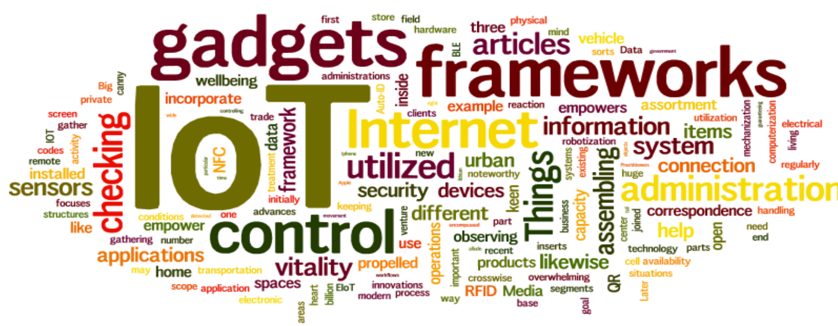
CS578: Internet of Things

6LoWPAN:
IPv6 over 802.15.4

Initial RFC: https://datatracker.ietf.org/doc/rfc4944/

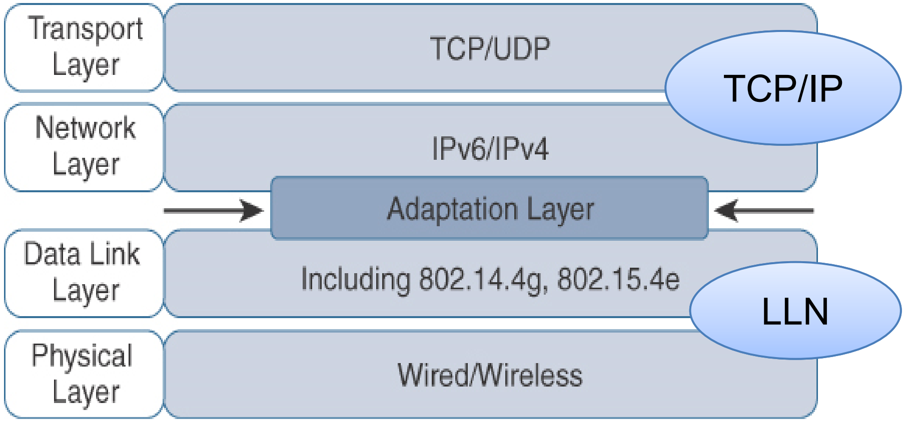


Dr. Manas Khatua
Assistant Professor, Dept. of CSE, IIT Guwahati
E-mail: manaskhatua@iitg.ac.in

"*Peace comes from within. Do not seek it without.*" – **Gautama Buddha**

6LoWPAN

IETF formed 6LoWPAN WG in 2004
to design the Adaptation Layer



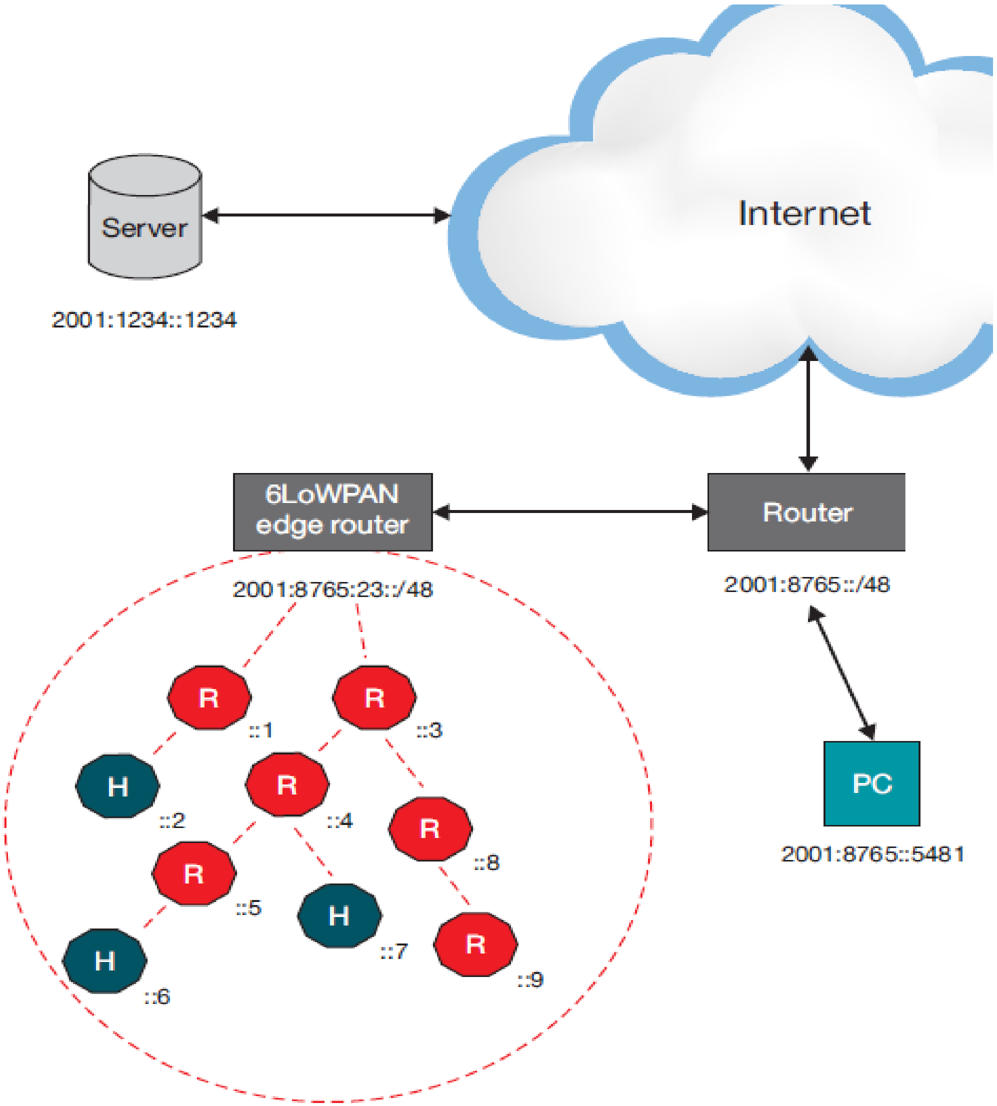
6LoWPAN: IPv**6** over **Lo**w-power **W**ireless **P**ersonal **A**rea **N**etworks

How to carry IPv6 packet efficiently within small link layer frames such as IEEE 802.15.4?

- IPv6 MTU to be **at least 1280 bytes** in length.
- 802.15.4's standard packet size of **127 octets**.

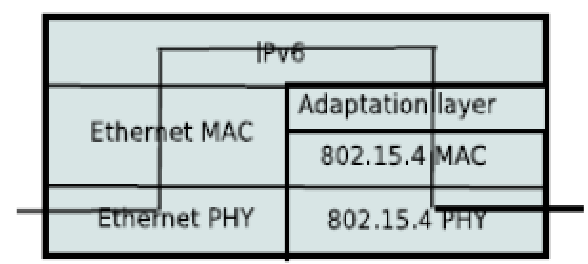
- Primary **goal**
  - even the smallest devices should have access to the IP
    - smallest devices ➔ low-power devices with limited processing capabilities.
- 6LoWPAN **defined**
  - encapsulation and header compression mechanisms
- 6LoWPAN **Applications**:
  - General Automation, Home automation, Smart Grid, Industrial monitoring, Smart Agriculture, etc.

6LoWPAN Edge Router



By communicating natively with IP, 6LoWPAN networks are connected to other networks **simply using IP routers at the edge.**

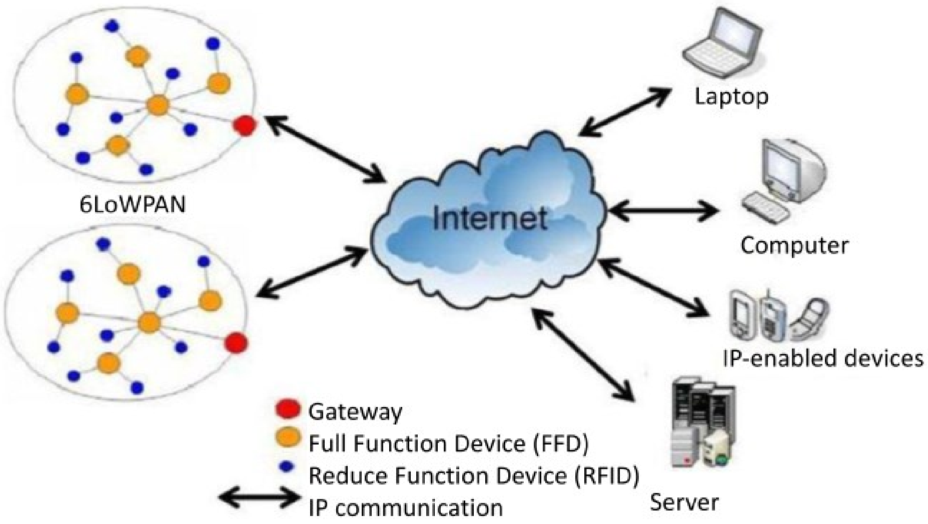
Edge router



Dual Stack in Edge router

Source: https://www.ti.com/lit/wp/swry013/swry013.pdf?

6LoWPAN Architecture



BENEFITS

- Ideal to create mesh networks
- Direct connectivity to the Internet
- Low power & Low data rates

The **utility of a mesh network** over other network types, such as a hub-and-spoke network, is that if a node is too far away from the hub, it can still communicate via a closer node until it reaches a router.

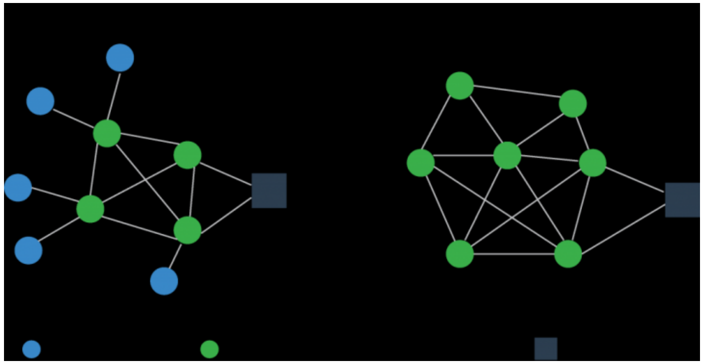
Other Advantages:

- Increased stability by avoiding single point failure
- Increased range by using multi-hop communication
- Direct communication between nodes
- Less power is needed for each node as all nodes need not send signal to central access point

Source: https://www.e-spincorp.com/what-is-6lowpan-and-its-functions/

What is mesh network?

A mesh network is a network in which a device or node is linked with all other nodes or with a sub-set of nodes directly.



6LoWPAN Advantages

Open IP Standard

- Use open standard such as TCP, UDP, HTTP, CoAP, MQTT, WebSocket
- End-to-End IP addressable nodes
- No gateway needed.
  - A router connects the 6LoWPAN network to IP

Mesh Routing

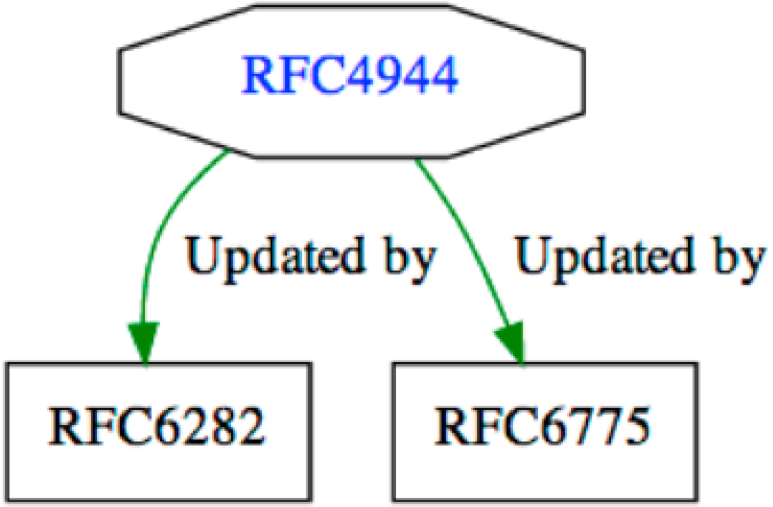
- One-to-many / many-to-one routing
- Robust and Scalable
- Self healing
- Flexible

Multiple PHY Support

- Freedom of frequency band and physical layer
- Can be used across multiple communication platform
  - (ex. Ethernet / WiFi / 802.15.4 / Sub-1 GHz)
- Interoperability at the IP level

RFCs

6LoWPAN IETF group developed a **base specification RFC 4944** →
"Transmission of IPv6 Packets over IEEE 802.15.4 Networks"



This document specifies an IPv6 **Header Compression** format for IPv6 packet delivery in 6LoWPAN

This document describes simple optimizations to IPv6 **Neighbor Discovery**, its **addressing schemes**, and duplicate address detection for 6LoWPAN

RFC4919: This document describes the overview, assumptions, problem statement, and goals for transmitting IP over IEEE 802.15.4 networks.

RFC6568: This document investigates potential application scenarios and use cases for LoWPANs

RFC6606: This document provides the problem statement and design space for 6LoWPAN routing. Defines how 6LoWPAN formation and multi-hop routing could be supported.

Motivation to use IPv6

Benefits of IP over IEEE 802.15.4 Network (RFC 4919):

- The pervasive nature of IP networks allows use of existing Infrastructure.
- IP-based technologies already exist, and are well-known
- Open and freely available specifications (v/s. Closed proprietary solutions).
- Tools for diagnostic, management already exist.
- IP-based devices can be connected readily to IP-based networks, without gateways or proxies.

Why IPv6? →

- Large simple address (2^128 address space)
  - Network ID + Interface ID
  - Plenty of addresses; easy to allocate and manage
- Auto-configuration and Management
  - ICMPv6
- Integrated bootstrap and discovery
  - Neighbors, routers, DHCP
- Global scalability
  - 128 Bit Addressing = 3.4*10^38 unique addresses

IPv6 Challenges

1. Header Size Calculation

Frame Header (25)	LLSEC (21)	IPv6 Header (40)	UDP (8)	Payload (33)

- IPv6 header: 40 octets
- UDP header: 8 octets
- 802.15.4 MAC frame header: up to 25 octets (with null security)

  or 25+21=46 octets (with AES-CCM-128)

✓ With 802.15.4 frame size of 127 octets, we have following space left for application data!

- 127-(8+40+25) = 54 octets (in case of null security)
- 127-(8+40+46) = 33 octets (in case of AES-CCM-128)

Cont…

2. IPv6 Maximum Transmission Unit (MTU) Requirements

- ✓ IPv6 requires that links should support an MTU of 1280 octets
  - So, Link-layer fragmentation & reassembly is needed

3. IP assumes that devices are always 'ON' i.e. active

- ✓ But embedded devices may not have enough power and duty cycles

4. Multicast support

- ✓ IEEE 802.15.4 & other low power radios do not support multicast (as it is expensive)

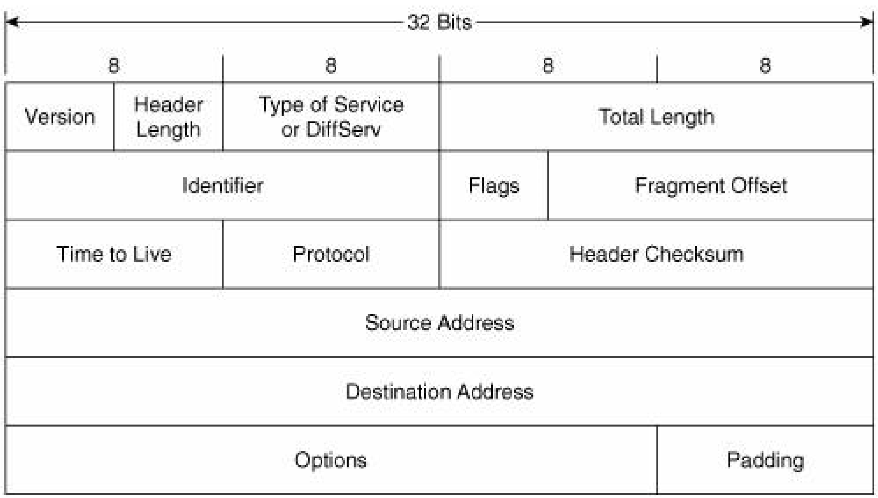
Main Goals of 6LoWPAN Design

- Define adaptation layer to match IPv6 MTU requirements
  - by fragmentation/reassembly
- Specify methods to do IPv6 Address formation
  - by stateless address auto configuration
- Specify/use header compression schemes.
  - by specific compression techniques
- Methods for mesh broadcast/multicast below IP
  - by layer 2 networking and forwarding mechanism

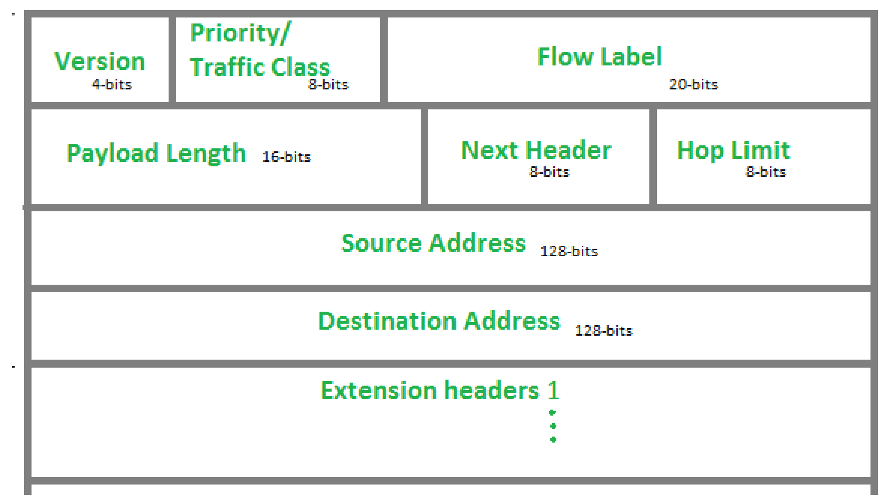
Adaptation Layer

It mainly performs the following functionalities:

- ✓ **Header Compression** **->** Compresses 40B IPv6 and 8B UDP headers
- ✓ **Fragmentation & Reassembly** **->** when MTU of 802.15.4 and IPv6 does not match.
- ✓ **Stateless Autoconfiguration** **->** Devices inside 6LoWPAN generate their own IPv6 address

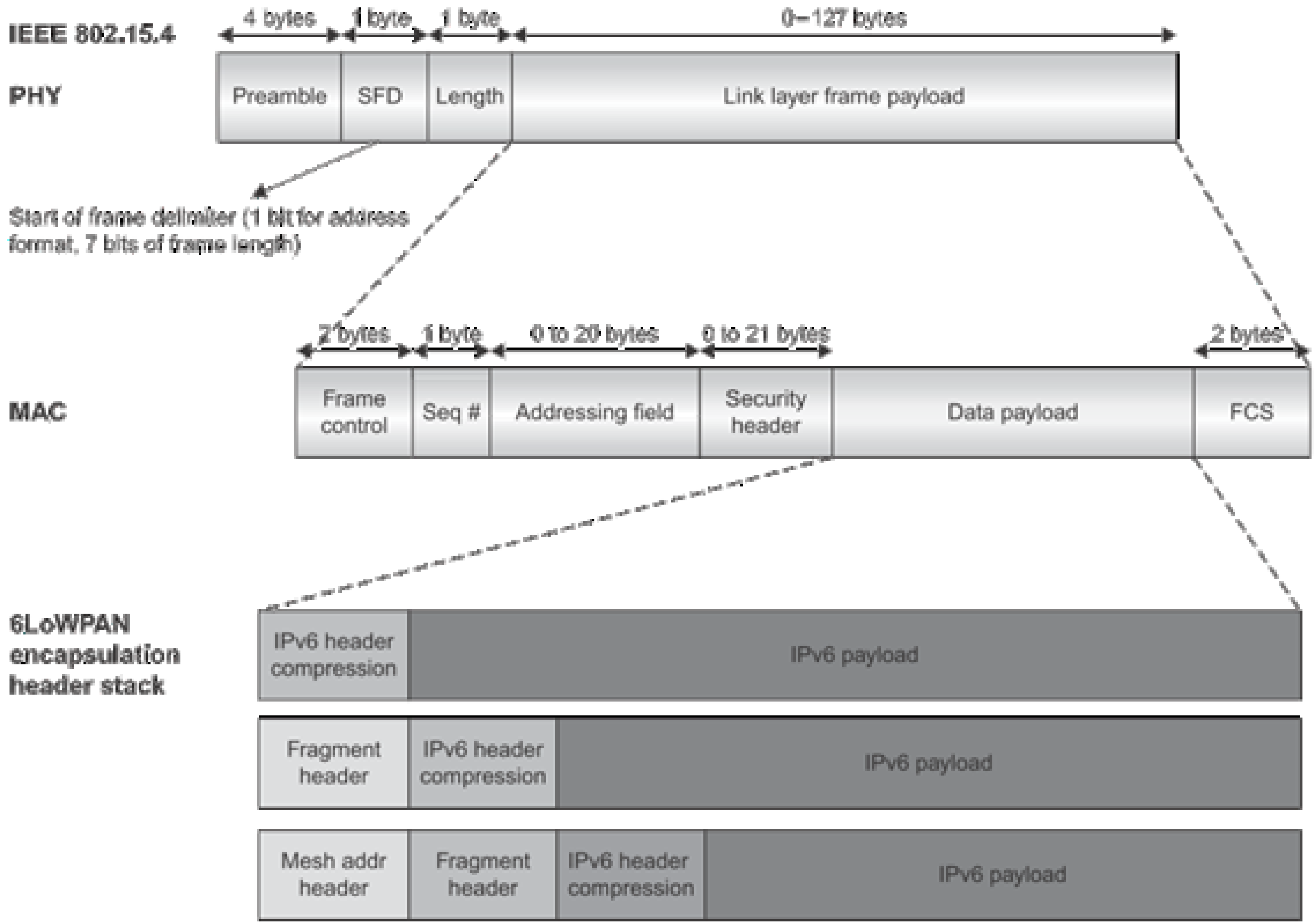


IPv4 header



IPv6 header (min 40 Byte)

LoWPAN Encapsulation

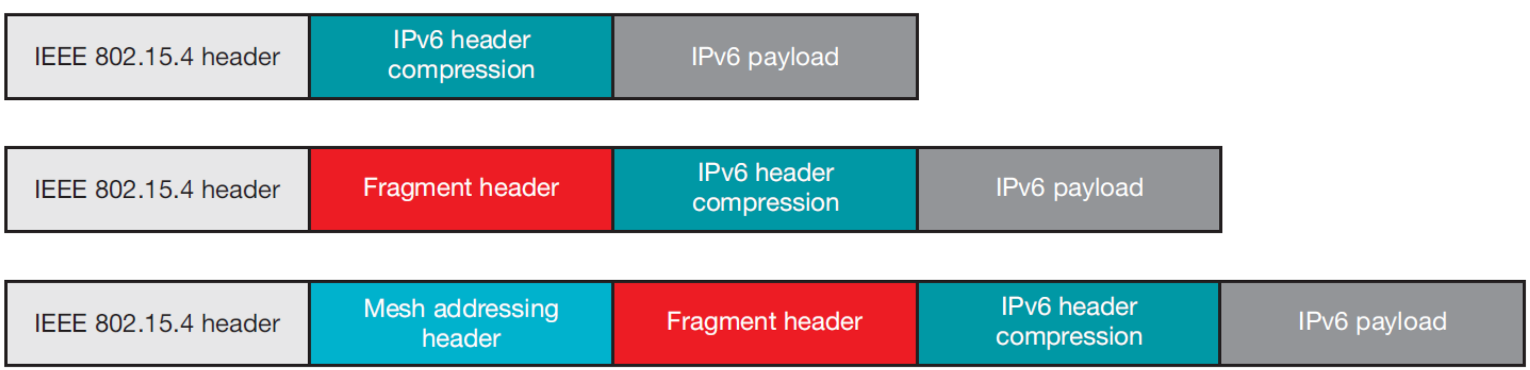


LoWPAN encapsulation are the payload in the IEEE 802.15.4 MAC protocol data unit (PDU).

Stacked Headers

- 6LoWPAN uses concept of
  - stacked headers
    - ✓ when dispatch header is used to indicate the sub-header type that immediately follows
  - extension headers
    - ✓ when the next header field is used to indicate the header type that immediately follows
- 6LoWPAN headers define the capability of each.
- Few 6LoWPAN headers are :
  - *Mesh addressing,*
  - *Fragmentation,*
  - *Header compression,*

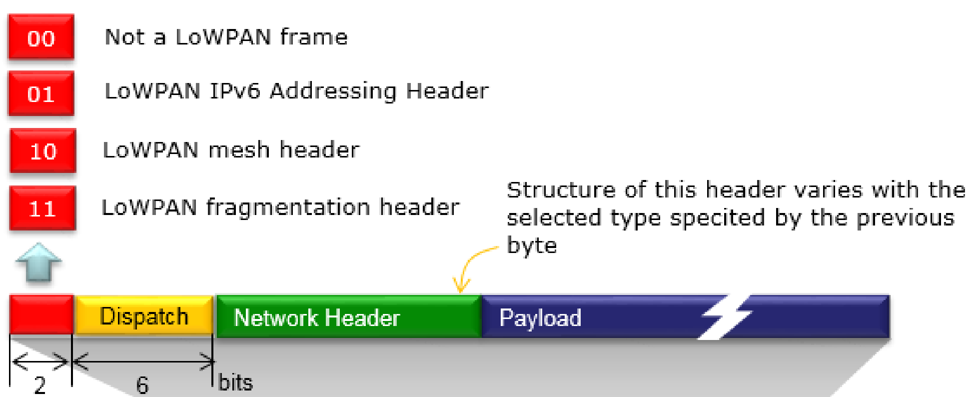
If more than one sub-header is used in the same IPv6 packet, they must follow the order.



6LoWPAN Headers

- **First byte** of each header (i.e. **dispatch byte**) identifies the **nature of each header**

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)



Dispatch Type & Header

```
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|0 1| Dispatch   |  type-specific header
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

- ✓ Dispatch type defined by 1st & 2nd bits
  - ✓ Dispatch means→ identifies type of header immediately following the Dispatch Header
  - ✓ Type-specific header → it is determined by full Dispatch Header.

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)

Cont…

- **Each header** in the stack starts with
  - a header type field, and
  - followed by zero / more type specific header fields

```
A LoWPAN encapsulated IPv6 datagram:

    +---------------+-------------+---------+
    | IPv6 Dispatch | IPv6 Header | Payload |
    +---------------+-------------+---------+

A LoWPAN encapsulated LOWPAN_HC1 compressed IPv6 datagram:

    +--------------+------------+---------+
    | HC1 Dispatch | HC1 Header | Payload |
    +--------------+------------+---------+

A LoWPAN encapsulated LOWPAN_HC1 compressed IPv6 datagram that
requires mesh addressing:

    +-----------+-------------+--------------+------------+---------+
    | Mesh Type | Mesh Header | HC1 Dispatch | HC1 Header | Payload |
    +-----------+-------------+--------------+------------+---------+

A LoWPAN encapsulated LOWPAN_HC1 compressed IPv6 datagram that
requires both mesh addressing and fragmentation:

    +-------+-------+-------+-------+---------+---------+---------+
    | M Typ | M Hdr | F Typ | F Hdr | HC1 Dsp | HC1 Hdr | Payload |
    +-------+-------+-------+-------+---------+---------+---------+
```

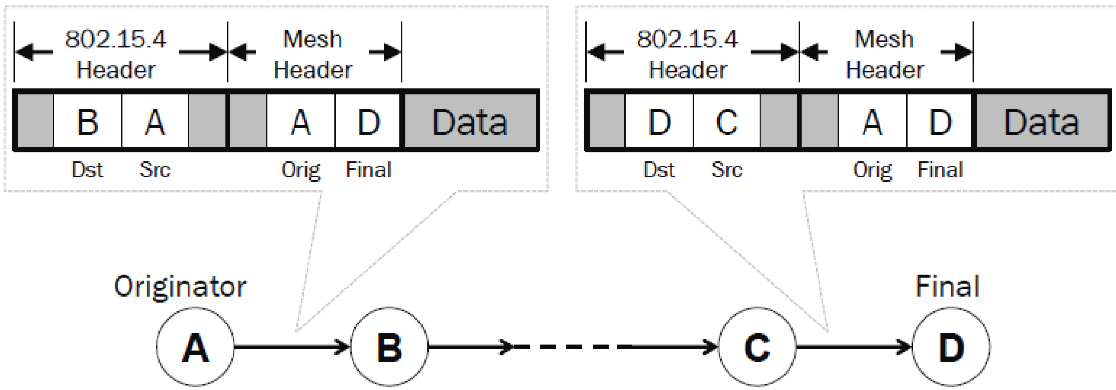
Mesh Addressing Type & Header

```
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|1 0|V|F|HopsLft| originator address, final address
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Dispatch Header

- ✓ 1^{st} & 2^{nd} bits = 10.
  - ✓ OA : link layer address of originator.
  - ✓ FDA : link layer address of final-destination
  - ✓ V: 0 => if OA is 64-bit EUI address
    1 => if OA is16-bit short address
  - ✓ F: 0 => if FDA is 64-bit EUI address
    1 => if FDA is16-bit short address
  - ✓ HopsLft: 4 bit, decremented by each forwarding node

Cont…

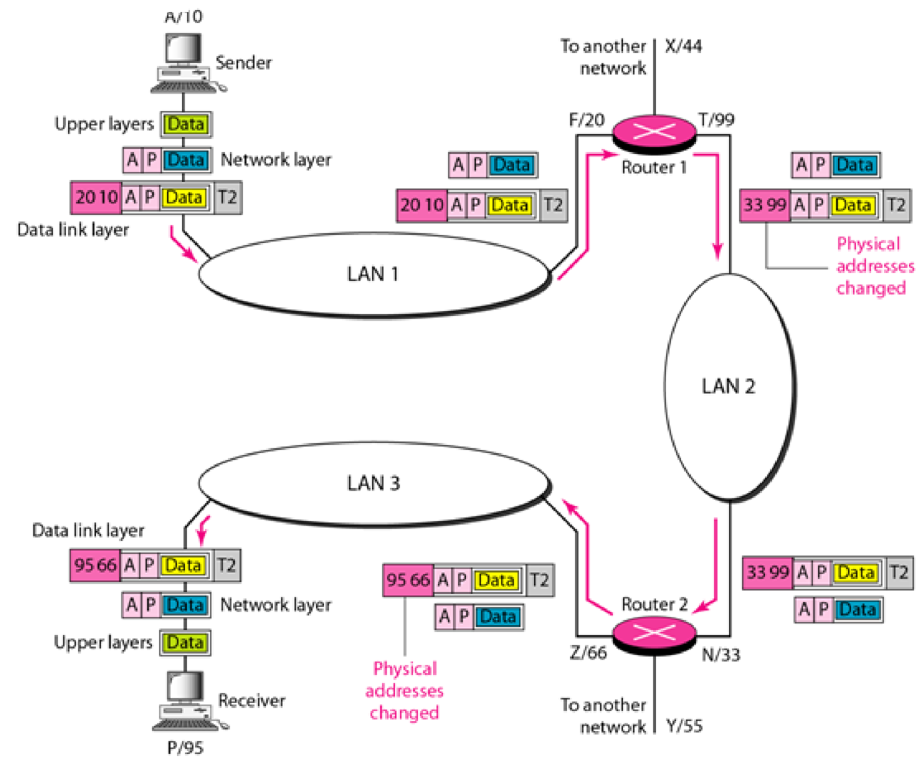


Routing by Mesh Header

Example of Mesh Routing header.

- Mesh networking is required to extend the network into multi-hop scenario

Data packet routing in TCP/IP network



Fragmentation Type & Header

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|1 1 0 0 0|    datagram_size    |         datagram_tag          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 \_ dispatch  _/
```

First Fragment

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|1 1 1 0 0|    datagram_size    |         datagram_tag          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|datagram_offset|
+-+-+-+-+-+-+-+-+
 \_ dispatch  _/
```

Subsequent Fragments

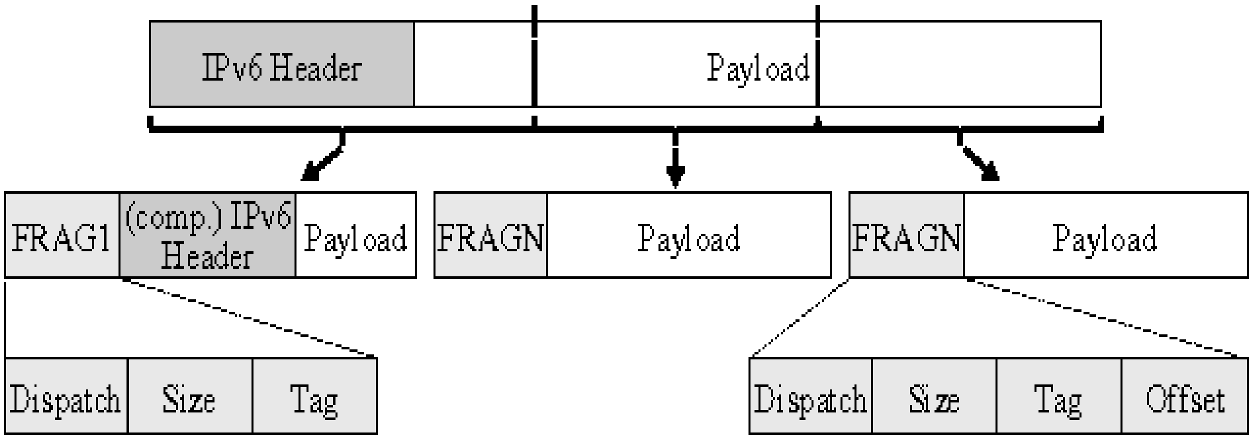
Dispatch: identifies the type of the immediate next headers
Datagram size (11 bits): encode the size of entire IP packet (after IP layer fragmentation, if any).

Datagram tag (8 bits): same for all *link fragments* of a payload, but different for two IPv6 payload.
Datagram offset (11 bits): present only in subsequent fragments

Fragmentation and Reassembly

Fragmentation Principles (RFC 4944)

- When an IPv6 packet exceeds link-layer payload size then segments the packet into fragments.



6LoWPAN packet structure of FRAG1 and FRAGN

Tag: it is used to identify all fragments of a IPv6 datagram

Offset: It identifies the relative position of the received fragment from the beginning of the payload datagram to allow out-of-sequence delivery.

Cont…

- ✓ Only the 1st fragment carries end-to-end routing information.
- ✓ 1st fragment carries a header that includes :
  - datagram size, datagram tag .
- ✓ Subsequent fragments carry
  - datagram size, datagram tag, offset.
- ✓ Time limit for reassembly is 60 seconds.
- ✓ For a lost fragment, we need to resend entire set of fragments.

Addressing in 6LoWPAN

- 128-bit IPv6 address Interface ID (IID)

  ✓ **64-bit prefix** + **64-bit IID**

Identifies the network you are on and where it is globally

- identifies the network interface
- must be unique for that network
- typically formed statelessly from the interface MAC address

- There are different kinds of IPv6 addresses

  ✓ Loopback (0::1) and Unspecified (0::0)

  ✓ Unicast with global (e.g. 2001::) or **link-local (FE80::) scope**

  ✓ Multicast addresses (starts with FF::)

  ✓ Etc.

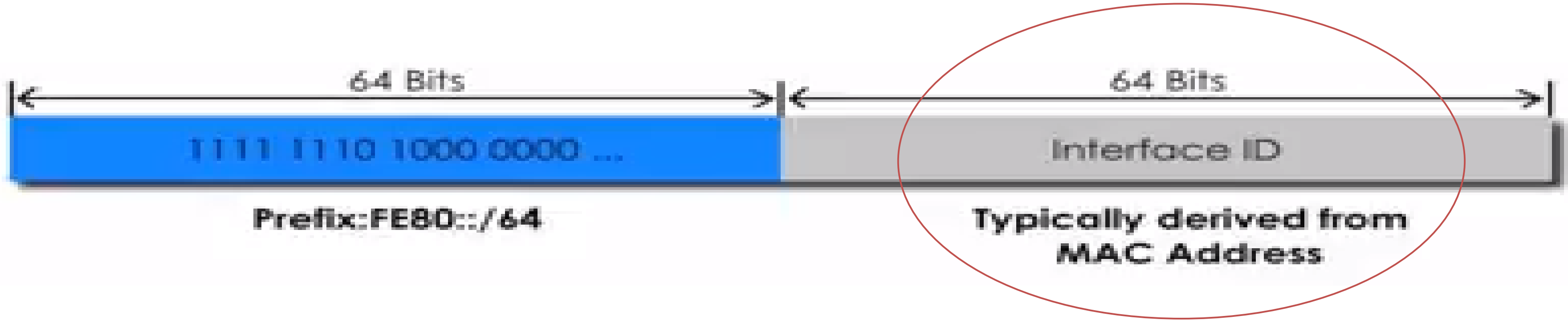
Link-local address in 6LoWPAN

A link-local address is a network address that is valid only for communications within the network segment or the broadcast domain that the host is connected to.

In IPv6, traditionally, FE80::/10 is used to represent link-local address.

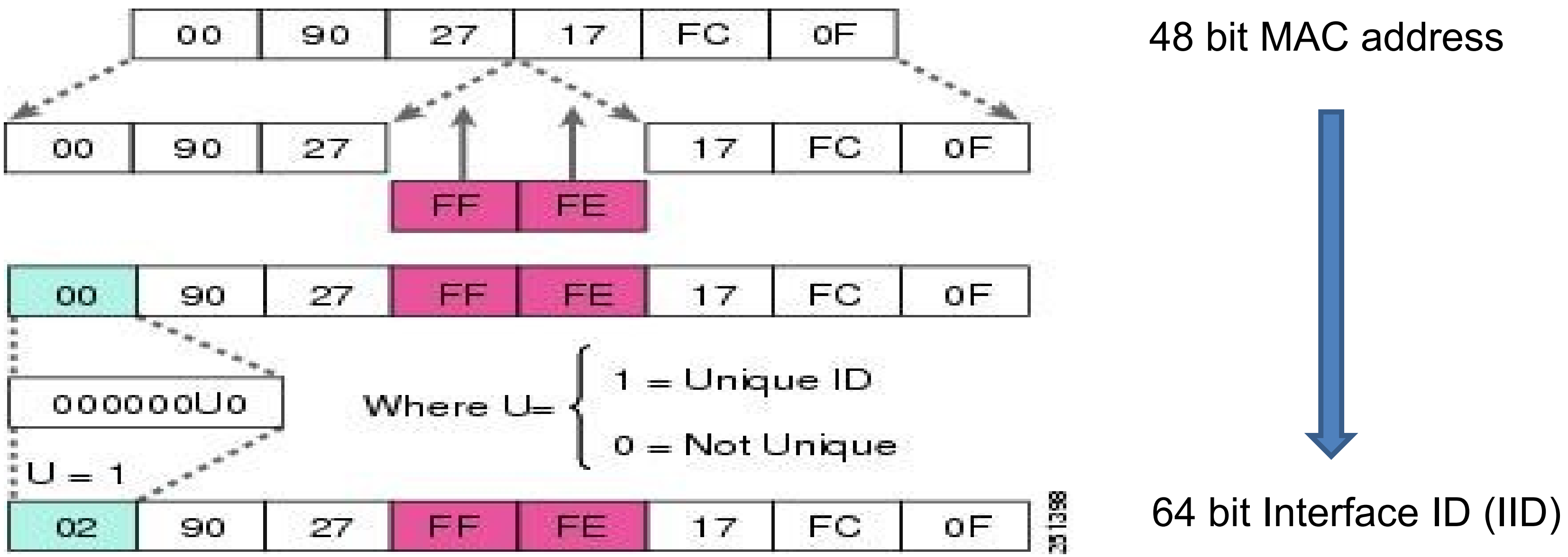
How does a host generate a *link-local address* in 6LoWPAN?

- ✓ Generated when a computer runs IPv6 boots up
  - ➢ Valid only for communication on a local network
  - ➢ Always have a prefix FE80::/64 ← mapped with PAN ID



64-bit IID generation from MAC address

Generating IID (EUI-64) from 48-bits MAC address (i.e. device address).



64-bit IID from 16-bit short address

All 802.15.4 devices have an IEEE EUI-64 address typically.
But 16-bit short addresses are also possible.

How to form the IID if an IoT device has 16-bit short address?

In these cases, a "pseudo 48-bit address" is formed first, and then EUI-64 interface id is formed from the pseudo 48-bit MAC address.

- 1st step: concat <16 bit PAN ID :16 zero bits>
- 2nd step: concat <32 bits in step:16 bit short address>
- 3rd step: 48 bits MAC address => 64 bit Interface ID

Stateless Auto-Configuration in IPv6

- It defines
  - ✓ how to obtain an IPv6 interface identifier (IID) from other known information
    - ➢ Uses both local and non-local information to generate its address.

Note: The **stateful** auto-configuration protocol allows hosts to obtain addresses and other configuration information from a server. So, stateless and stateful complement each other.

✓ Advantages:

- Allows a node to connect to the Internet without DHCP server
- Helps in header optimization

IPv6 address:

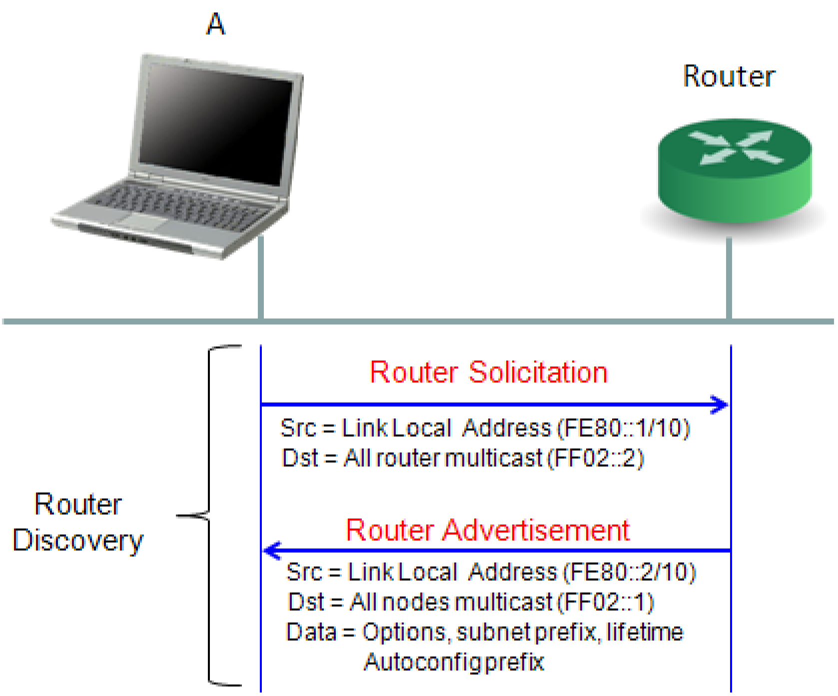
✓ Addresses are 128 bit long

- Divided into 8 hextets, each hextet is 16 bit
- Each character is 4 bit, a nibble

- A common configuration is a
  - 48-bit network prefix, 16-bit subnet mask, 64-bit host address/identifier.
    - e.g., 2001:1234:ABCD:0001:1023:FD45:0033:0002

Cont... (for IPv6)

Steps in stateless auto-configuration to obtain IPv6 address (128 bits):



- ✓ **Host** send Router Solicitation (RS) to all routers
- ✓ **Routers** reply with Router Advertisement (RA)
  - announces **prefix** used on link.
- ✓ **Host** generates address
  - by combining the **prefix** received and **host identifier** (EUI-64)
- ✓ So, IPv6 address (128 bit) is generated
  - ➢ Link-local address
- ✓ **Hosts** performs DAD activity
  - Duplicate Address Detection (DAD)
- ✓ If successful (i.e. not duplicate one), address becomes active

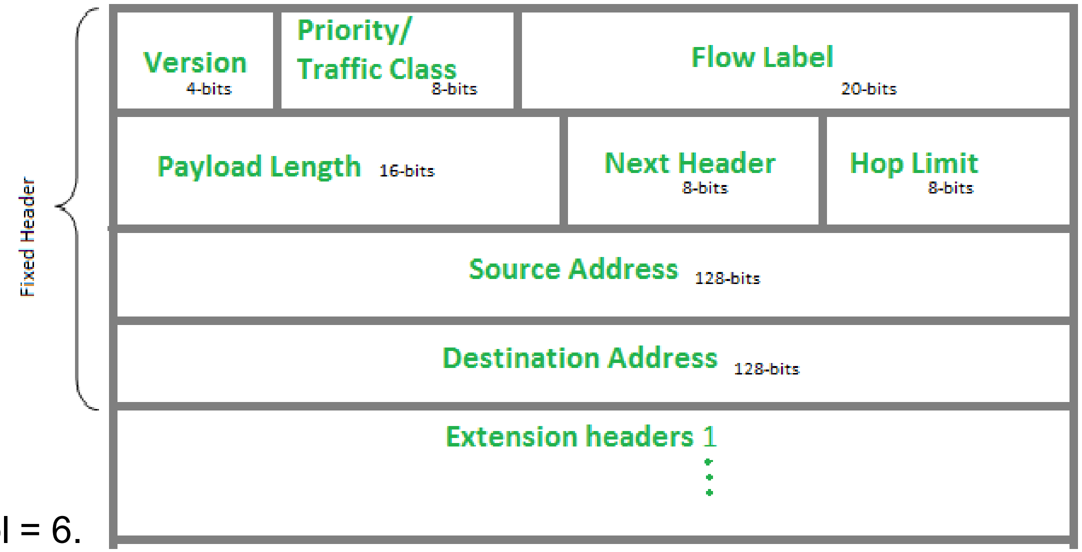
6LoWPAN Header Compressions

- **HC1 (for IP) and HC2 (for UDP) compressions**
  - Assume common values for header fields and define compact forms.
  - Reduce header size by omission

Omit headers that...

- can be reconstructed from L2 layer headers (i.e. redundant)
- contains information not needed/used in present context (i.e. unnecessary)

Cont…



IPv6 header

Version: version number of Internet Protocol = 6.

Priority / Traffic Class: indicates the class or priority of IPv6 packet

Flow Label: used by source to label the packets belonging to the same flow in order to request special handling by intermediate routers

Payload Length: size (in octets) of the rest of the packet that follows the IPv6 header

Next header: type of header that immediately follows the IPv6 header

Hop limit: Decremented by one by each node that forwards the packet.

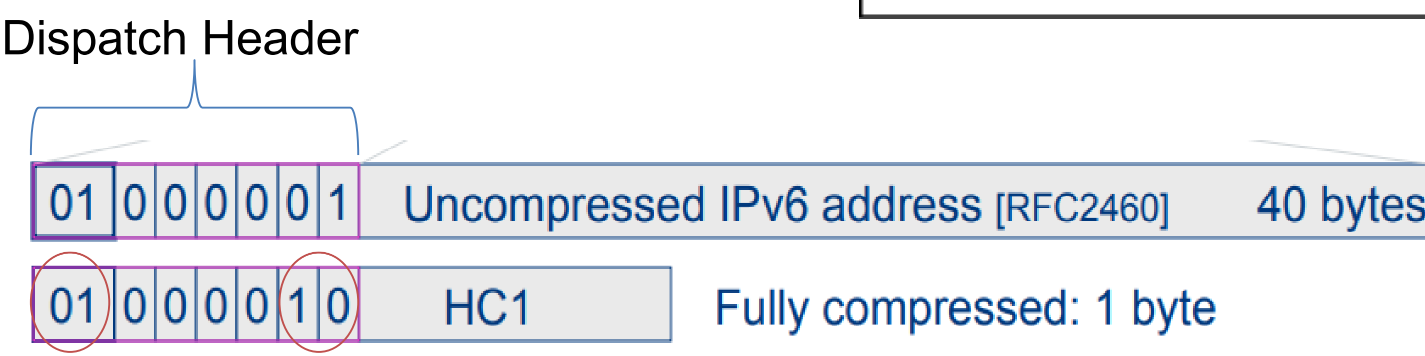
Source & Destination addresses: IPv6 addresses

Compression: HC1

HC1: Compresses IPv6 headers

IPv6 Header: 40-Byte

4 bits Version	4 bits Priority	24 bits Flow Label		
16 bits Payload Length			8 bits Next Header	8 bits Hop Limit
128 bits Source Address				
128 bits Destination Address				



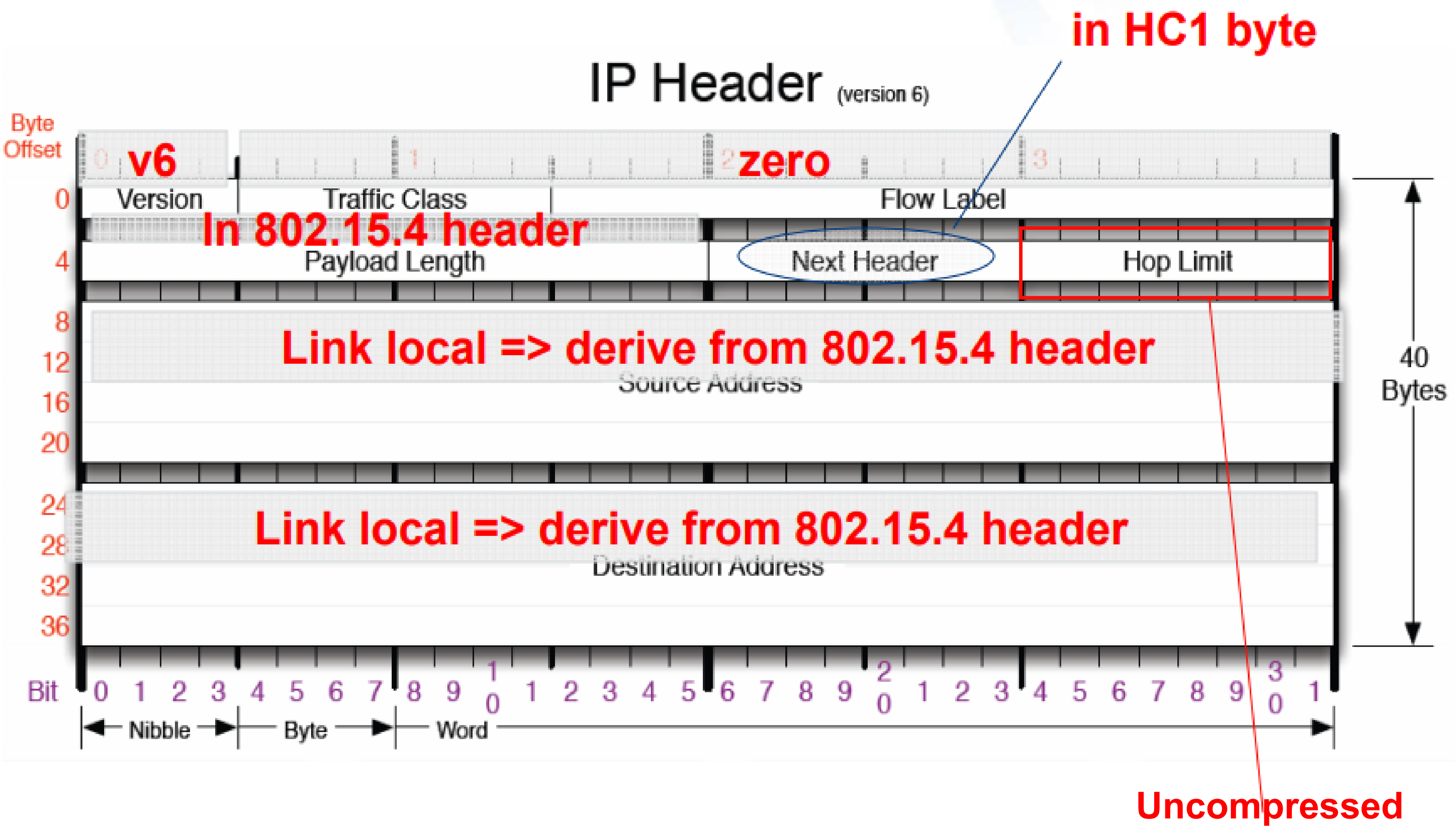
What are compressed fields?

- Source address **->** **Derived** from link address
- Destination address **->** **Derived** from link address
- Priority / Traffic class & Flow level **->** Zero (if ECN, DS, Flow level all zero)
- Next Header **->** Indicated in HC1 (TCP/UDP/ICMPv6)

Reduced to Zero Byte

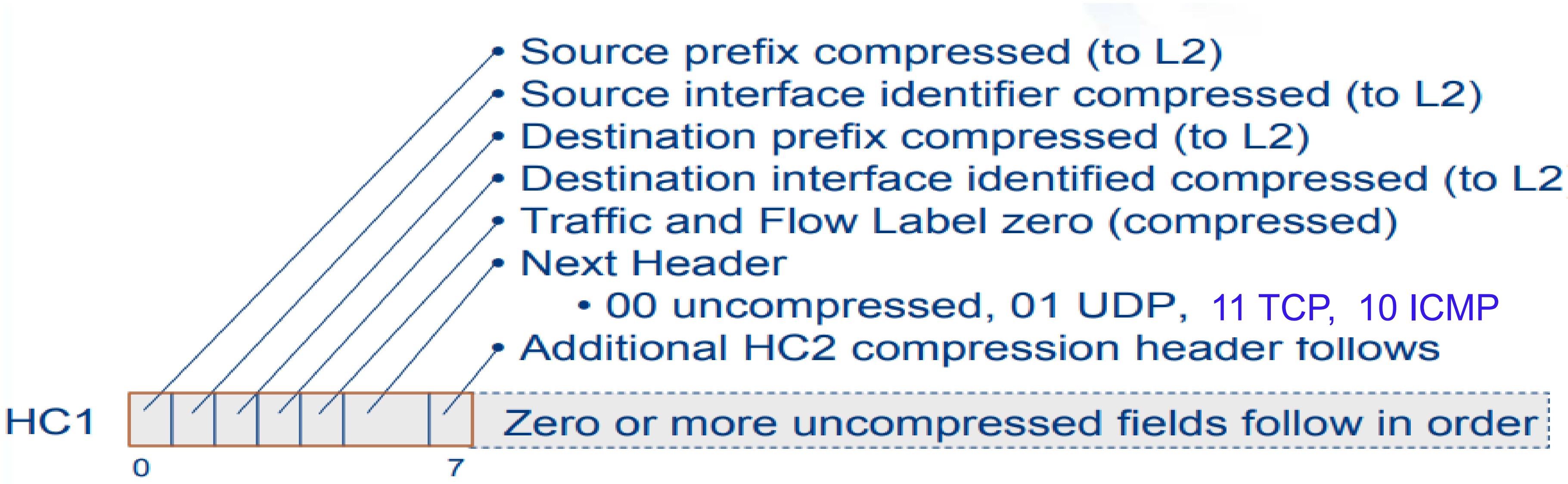
Cont…

Ipv6 Header compression



Cont...

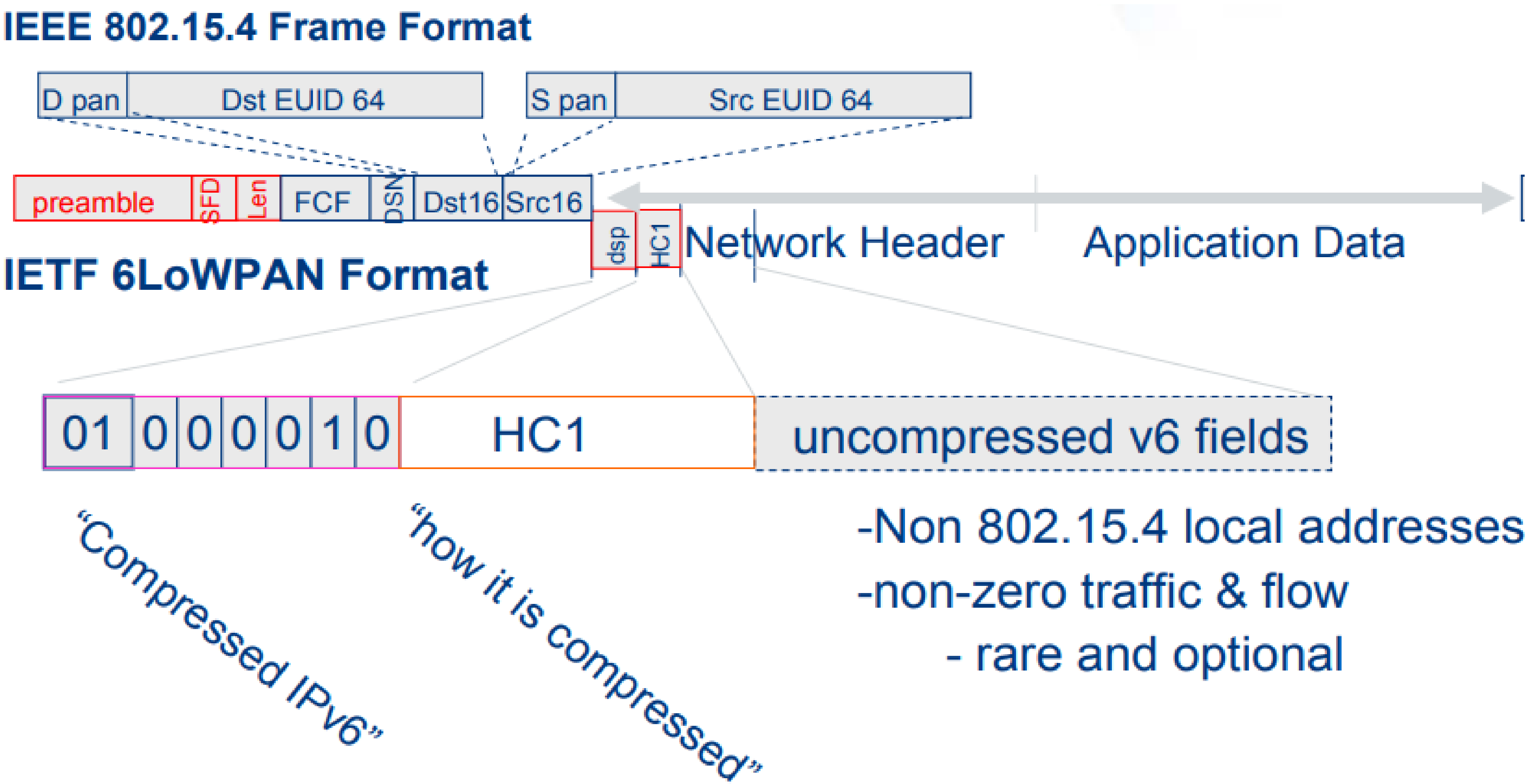
HC1 Compressed IPv6 Header



- ✓ IPv6 address <prefix64 || Interface ID64> for nodes in IEEE 802.15.4 subnet derived from the link address.
  - PAN ID maps to a unique IPv6 prefix
  - Interface ID64 generated from 48-bit MAC or 16-bit short address
- ✓ HopLimit is the only incompressible IPv6 header field.

Cont…

6LoWPAN: Compressed IPv6 Header



HC1 Encoding Field Values

IPv6 source address (bits 0 and 1):
- 00: PI, II
- 01: PI, IC
- 10: PC, II
- 11: PC, IC

IPv6 destination address (bits 2 and 3):
- 00: PI, II
- 01: PI, IC
- 10: PC, II
- 11: PC, IC

- PI: Prefix carried in-line
- PC: Prefix compressed (link-local prefix assumed).
- II: Interface identifier carried in-line
- IC: Interface identifier compressed

Traffic Class and Flow Label (bit 4):
- 0: not compressed; full 8 bits for Traffic Class and 20 bits for Flow Label are sent
- 1: Traffic Class and Flow Label are zero

Next Header (bits 5 and 6):
- 00: not compressed; full 8 bits are sent
- 01: UDP
- 10: ICMP
- 11: TCP

HC2 encoding (bit 7):
- 0: No more header compression bits
- 1: HC1 encoding immediately followed by more header compression bits per HC2 encoding format.

Compression: HC2

HC2:Compresses UDP Headers

UDP header format
[8 Byte]

Source port	Destination port
UDP length	Checksum

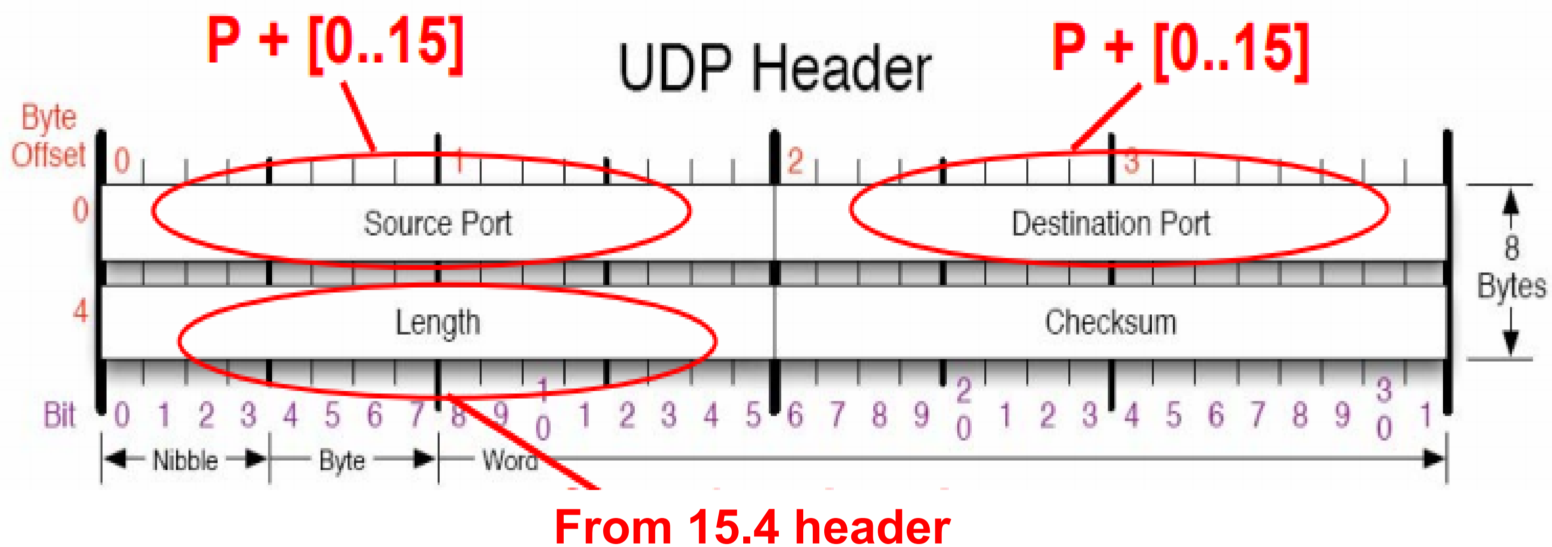
Reduced to

- ✓ Source port = P+4bits, P=61616
- ✓ Destination port= P+4bits, P=61616

} 1 Byte

- ✓ Length **derived** from IPv6 length
- ✓ Checksum is always carried inline

} 2 Byte



Limitations of HC1 & HC2

- ✓ LoWPAN_HC1 & LoWPAN_HC2 are insufficient for most practical uses.
  - ✓ Effective only for link-local unicast communication,

- ✓ So, they are usually not used for application layer data traffic in present times

So, RFC 6282 was proposed as an advancement

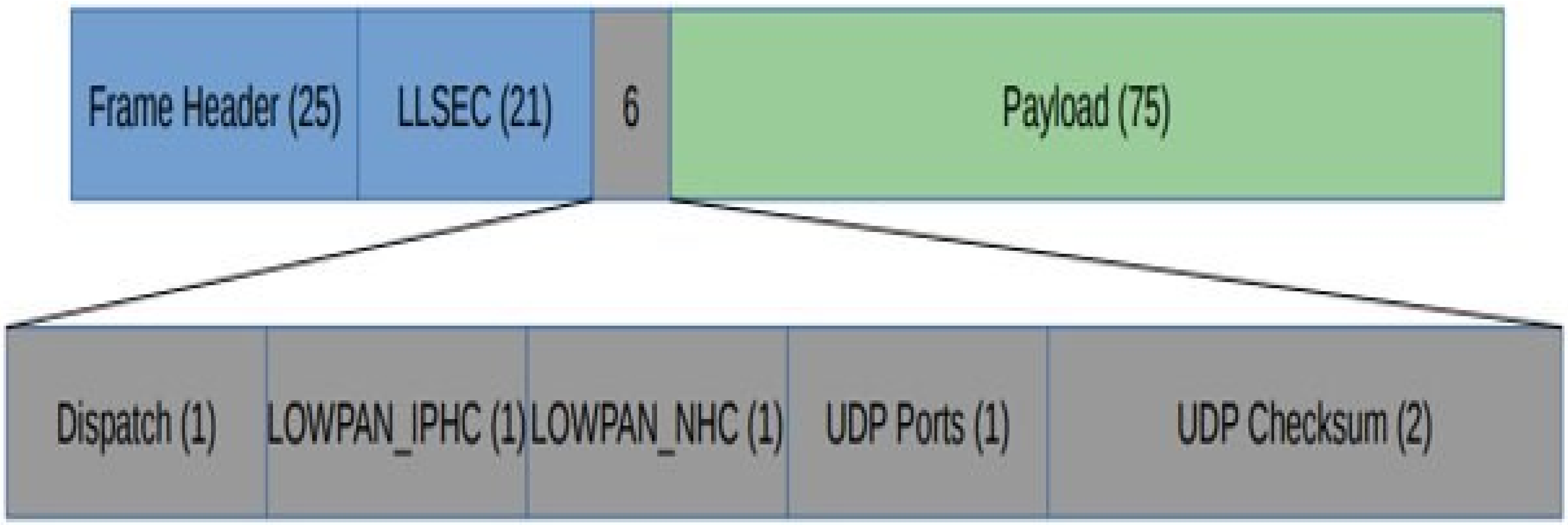
- Defines LoWPAN_IPHC
  - Not only link-local, compression for global and multicast addresses too
  - Compress header fields with common values:
    - version, traffic class, flow label, **hop-limit**

- Defines LoWPAN_NHC (for arbitrary next headers)
  - Adds ability to omit UDP checksum

❖ Possible to invent your own scheme if you have repeating usage patterns in your use case

The Header Size Solution

The **48-byte (IPv6 + UDP header)** could in the best cases be **reduced to 6 bytes.**

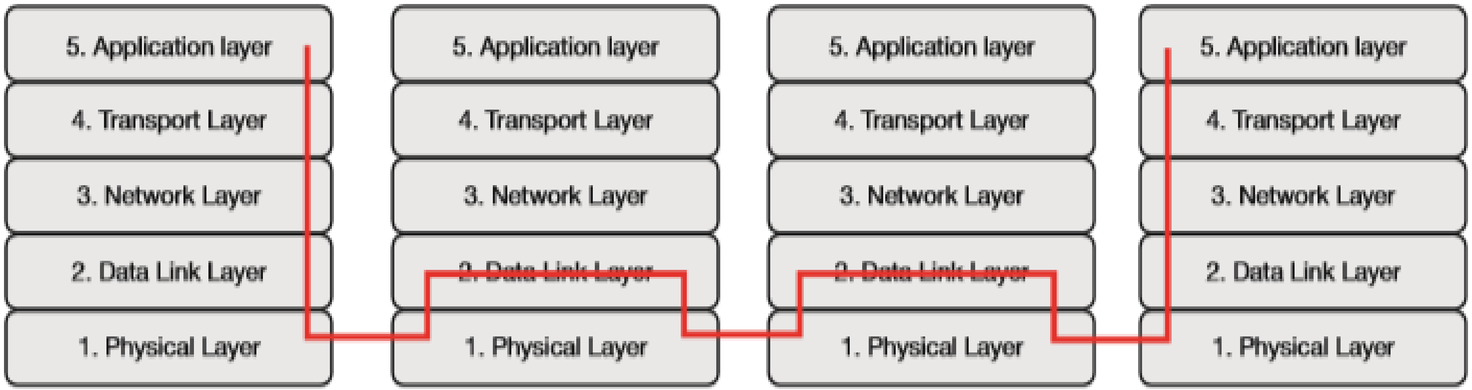


Routing Mechanisms

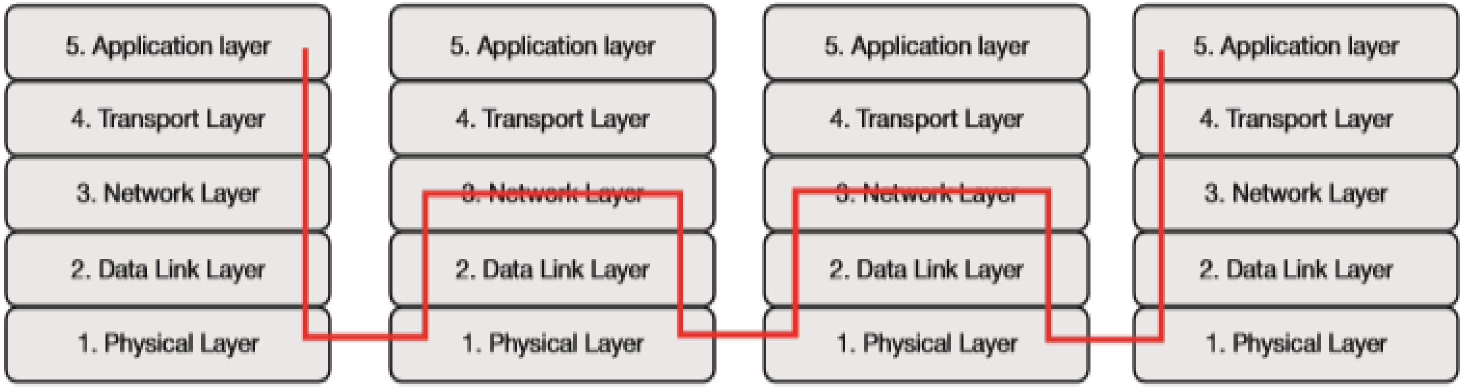
6LoWPAN supports two routing mechanisms (RFC 6606):

- Mesh-under
- Route-over

Mesh-under



Route-over



Cont…

Mesh-under

- ✓ Uses L2 addresses to forward data
- ✓ **Only edge router is the IP router**; other intermediate devices are mesh-under forwarder
- ✓ Individual fragments may take different paths.
- ✓ Suitable for small and local networks

```
      h    h
     /     |
6LBR --- m --- m --- h
          / \
        h    m --- h
             |
            / \
           m - m -- h
```

An Example of a Mesh-Under 6LoWPAN

Route-over

- ✓ Uses L3 addresses to forward data.
- ✓ **Each hop acts as an IP router** or 6LoWPAN router.
- ✓ All fragments are sent to same path as routing decision taken on per packet basis
- ✓ Suitable for all sized networks

```
      h    h
     /     |
6LBR -- 6LR --- 6LR --- h
        / \
       h  6LR --- h
           |
          / \
        6LR - 6LR -- h
```

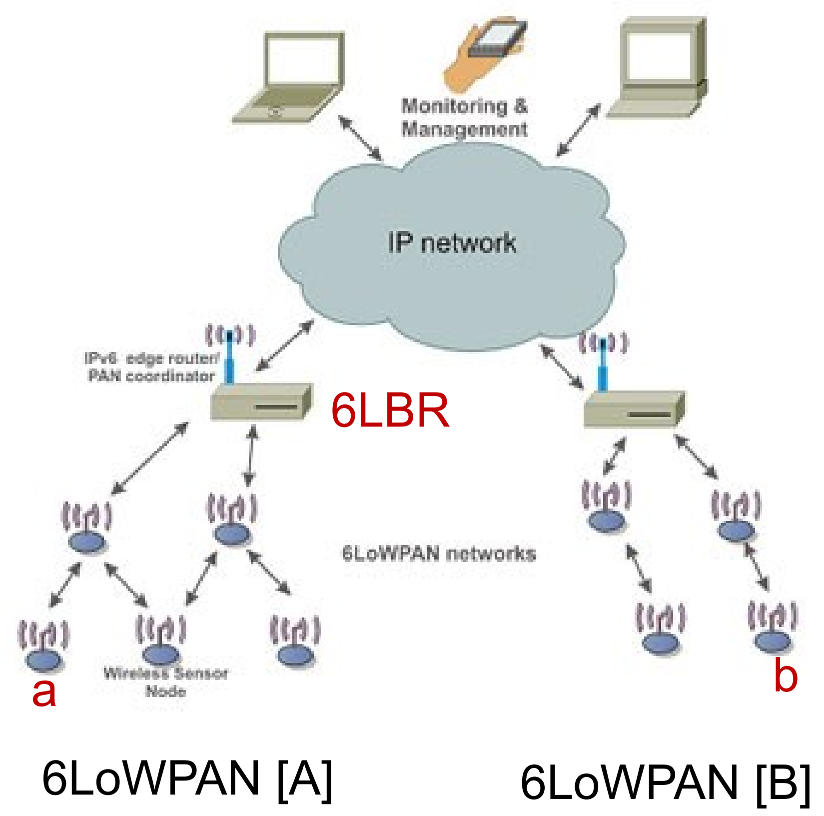
An Example of a Route-Over 6LoWPAN

Cont…

When multiple LoWPANs are formed with globally unique IPv6 addresses in the 6LoWPANs, and device "a" of LoWPAN [A] wants to communicate with device "b" of LoWPAN [B], the normal IPv6 mechanisms will be employed.

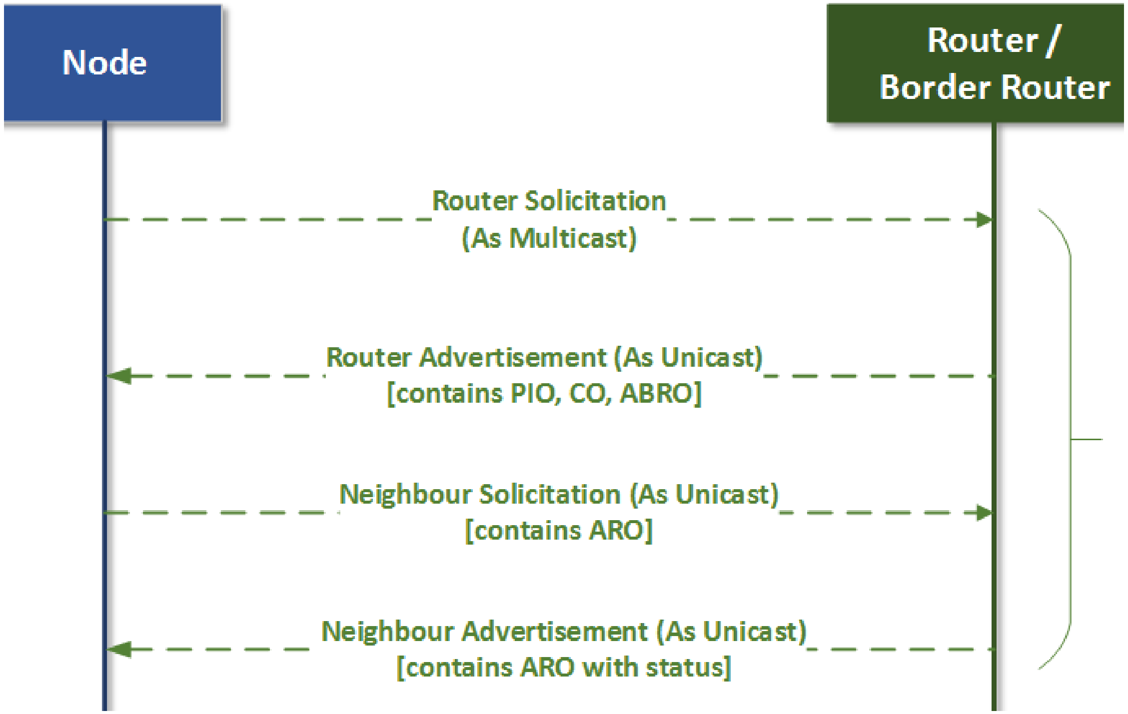
For route-over, the IPv6 address of "b" is set as the destination of the packets, and the devices perform IP routing to the 6LBR for these outgoing packets.

For mesh-under, there is one IP hop from device "a" to the 6LBR of [A], no matter how many radio hops they are apart from each other. This, of course, assumes the existence of a mesh-under routing protocol in order to reach the 6LBR.



Neighbour Discovery (ND) Protocol

- This helps the node to determine the neighbors in the vicinity and to select the best parent available.
- Uses ICMP Message
  - RS (Router Solicitation) , RA (Router Advertisement)
  - NS (Neighbour Solicitation) , NA (Neighbour Advertisement)



Prefix Information (PIO) : The prefix of the IPv6 address

Context Option (CO) : The compression technique to be used.

Authoritative Border Router Option (ABRO) : Border Router address

Address Registration Option (ARO) : link layer address of the node, & direct reachability to node

Cont...

Router Solicitation and Advertisement

1—ICMP Type = 133 (RS)

Src = link-local address (FE80::1/10)

Dst = all-routers multicast address (FF02::2)

Query = please send RA

2—ICMP Type = 134 (RA)

Src = link-local address (FE80::2/10)

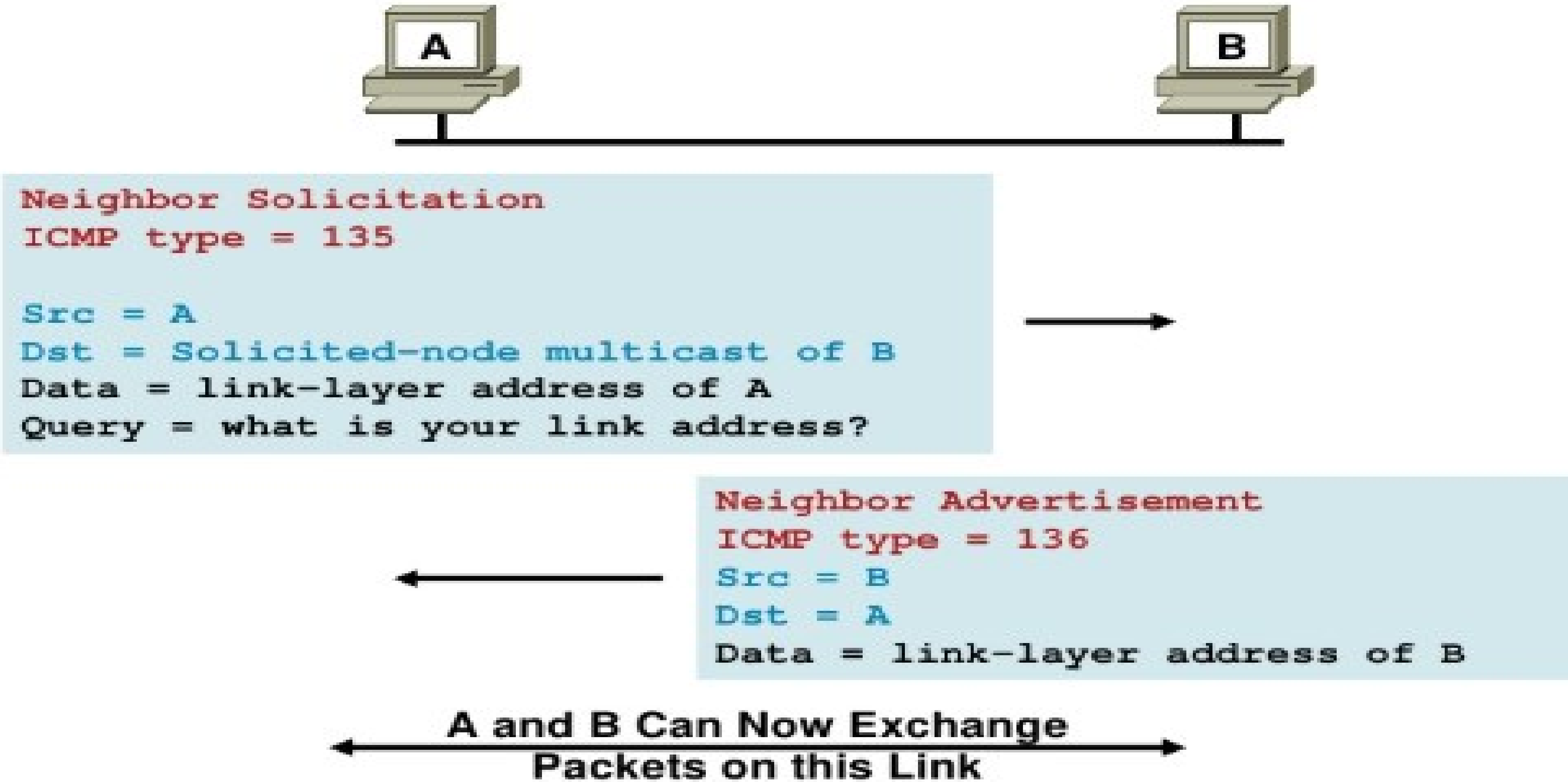
Dst = all-nodes multicast address (FF02::1)

Data = options, subnet prefix, lifetime, autoconfig flag

- Router Solicitations (RS) are sent by booting nodes to request RAs for configuring the interfaces
- Routers send periodic Router Advertisements (RA) to the all-nodes multicast address

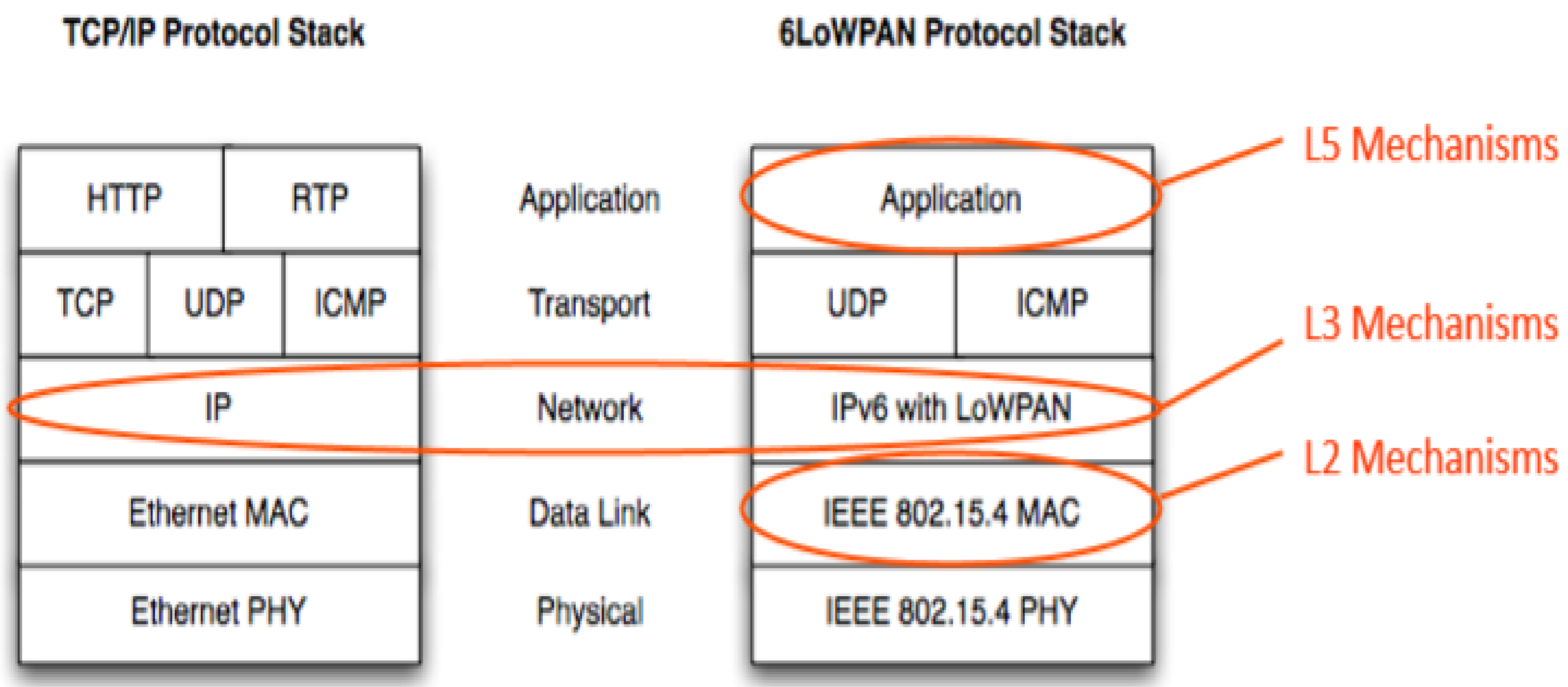
Cont...

Neighbor Solicitation and Advertisement



6LoWPAN Security

- Security is also important for IOT systems
  - ✓ It takes advantage of IEEE 802.15.4 **link layer security**
  - ✓ Also TLS (**Transport Layer Security**) mechanisms works for 6LoWPAN systems



Lessons Learned

- ✓ Motivation behind the development of Adaptation Layer
- ✓ 6LoWPAN
  - ✓ Architectures
  - ✓ RFCs
  - ✓ Stacked headers concept
  - ✓ Dispatch Header
  - ✓ Fragmentation Header
  - ✓ Mesh Routing Header
  - ✓ Compression Header
- ✓ Address Auto-configuration
- ✓ Header Compression
- ✓ Neighbour Discovery
- ✓ Data Forwarding : Mesh under & Route over
- ✓ 6LoWPAN Security

Thanks!