Embedded Internet and the Internet of Things WS 12/13

6. 6LoWPAN

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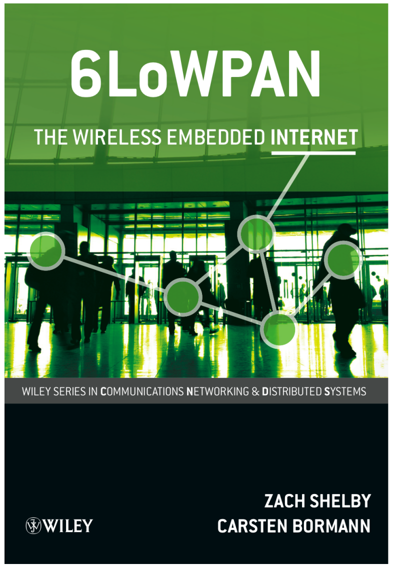
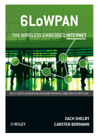
6LoWPAN: The Wireless Embedded Internet

Companion Lecture Slides



Figures on slides with book symbol from 6LoWPAN: The Wireless Embedded Internet, Shelby & Bormann, ISBN: 978-0-470-74799-5, (c) 2009 John Wiley & Sons Ltd



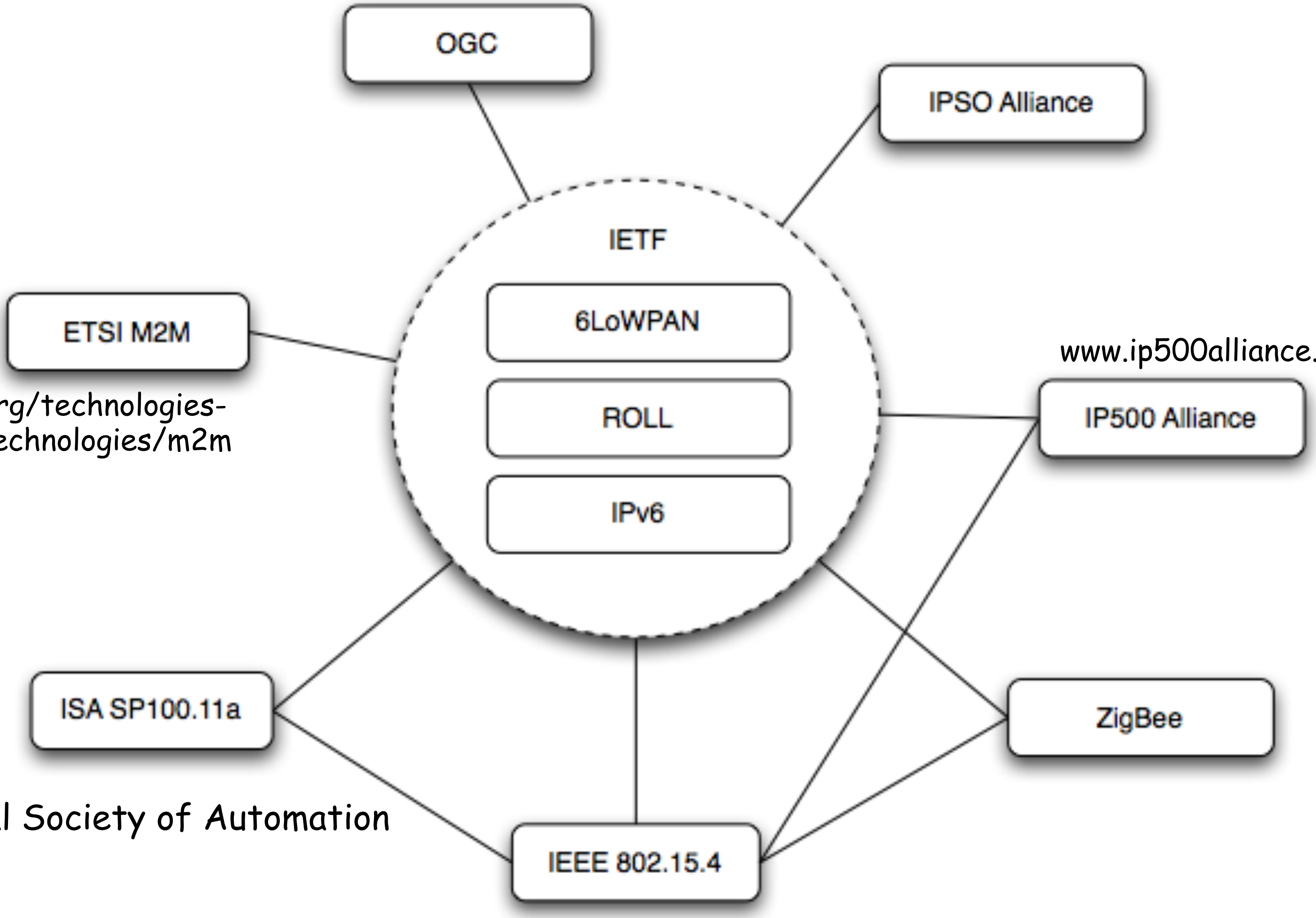
Outline

- Introduction to 6LoWPAN
- Refresher
  - The Internet Architecture & Protocols
  - Link Layer Technologies
- The 6LoWPAN Format
- Bootstrapping

Introduction to 6LoWPAN

Relationship of Standards

www.opengeospatial.org



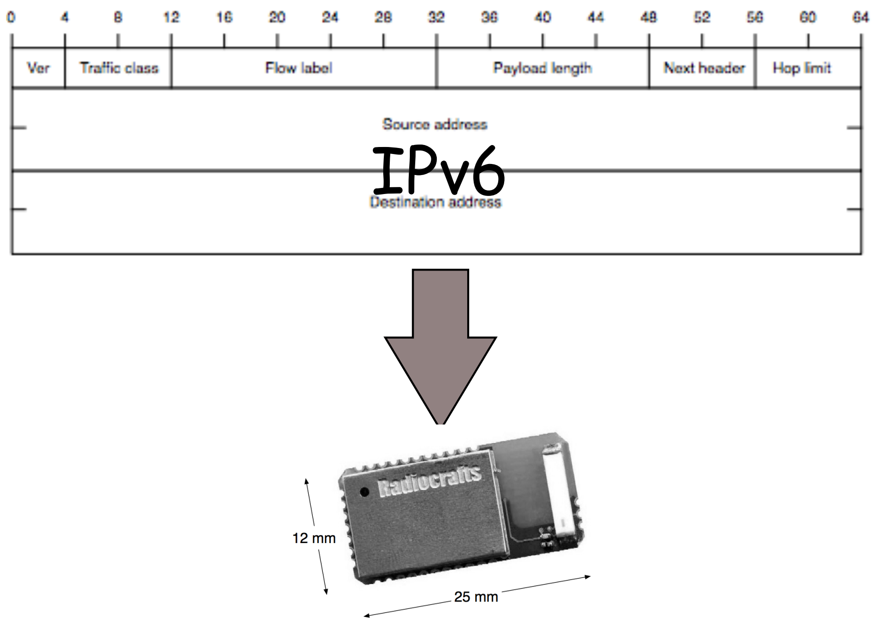
www.ip500alliance.org

www.etsi.org/technologies-clusters/technologies/m2m

International Society of Automation
www.isa.org

What is 6LoWPAN?

- IPv6 over Low-Power wireless Area Networks (LoWPAN)
  - LowPAN = LLN?



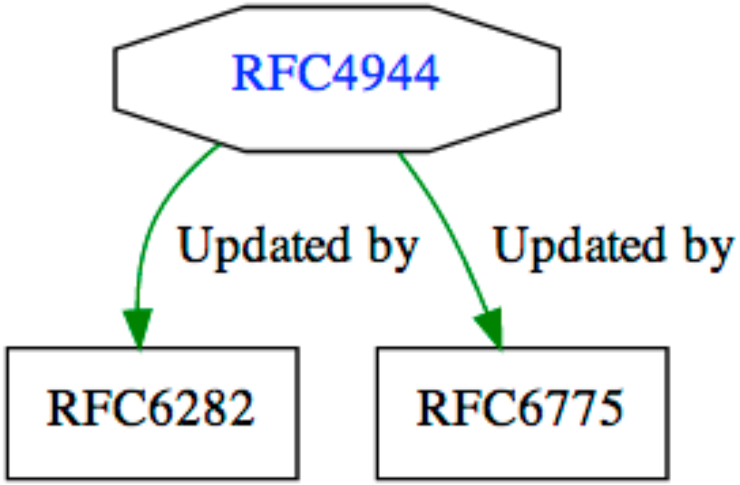
- Defined by IETF standards
- Stateless header compression
- Enables a standard socket API
- Minimal use of code and memory
- Direct end-to-end Internet integration
  - Multiple topology options

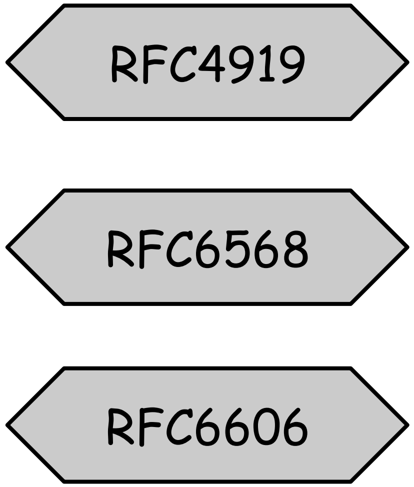
What is 6LoWPAN?

http://datatracker.ietf.org/wg/6lowpan/

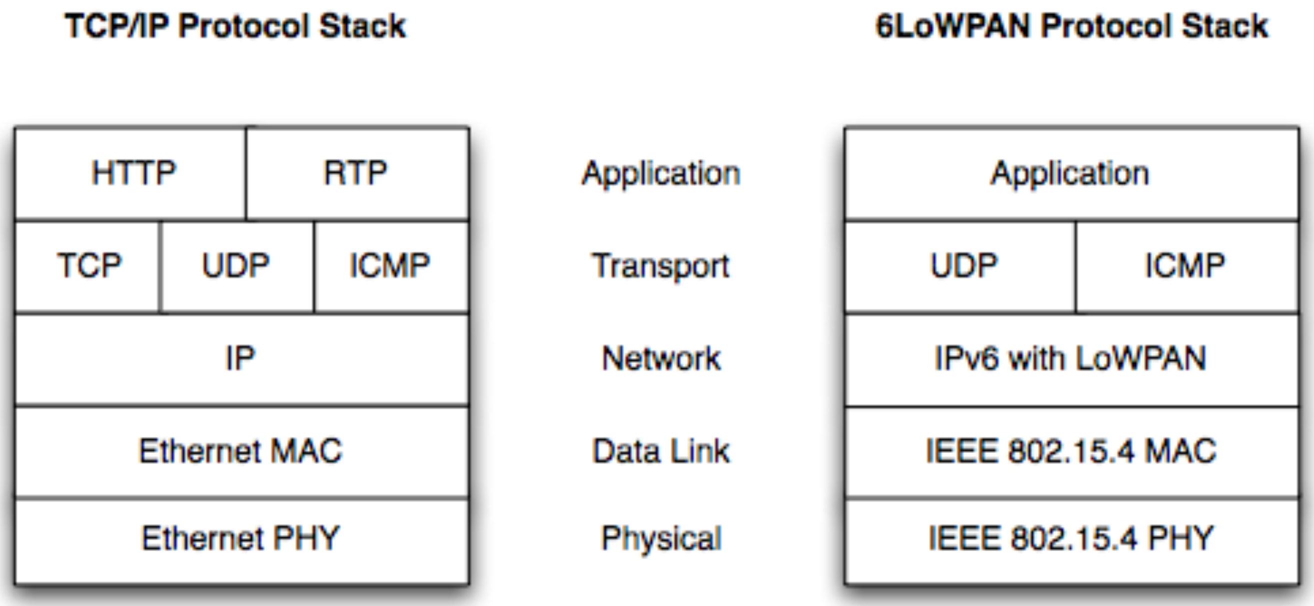
- RFC 4919 (draft-ietf-6lowpan-problem), 08/2007
  - IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs): Overview, Assumptions, Problem Statement, and Goals
- RFC 4944 (draft-ietf-6lowpan-format), 09/2007
  - Transmission of IPv6 Packets over IEEE 802.15.4 Networks
- RFC 6282 (draft-ietf-6lowpan-hc), 09/2011
  - Compression Format for IPv6 Datagrams over IEEE 802.15.4-Based Networks
- RFC 6775 (draft-ietf-6lowpan-nd), 11/2012
  - Neighbor Discovery Optimization for IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs)
- RFC 6568 (draft-ietf-6lowpan-usecases), 04/2012
  - Design and Application Spaces for IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs)
- RFC 6606 (draft-ietf-6lowpan-routing-requirements), 05/2012
  - Problem Statement and Requirements for IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) Routing

What is 6LoWPAN?



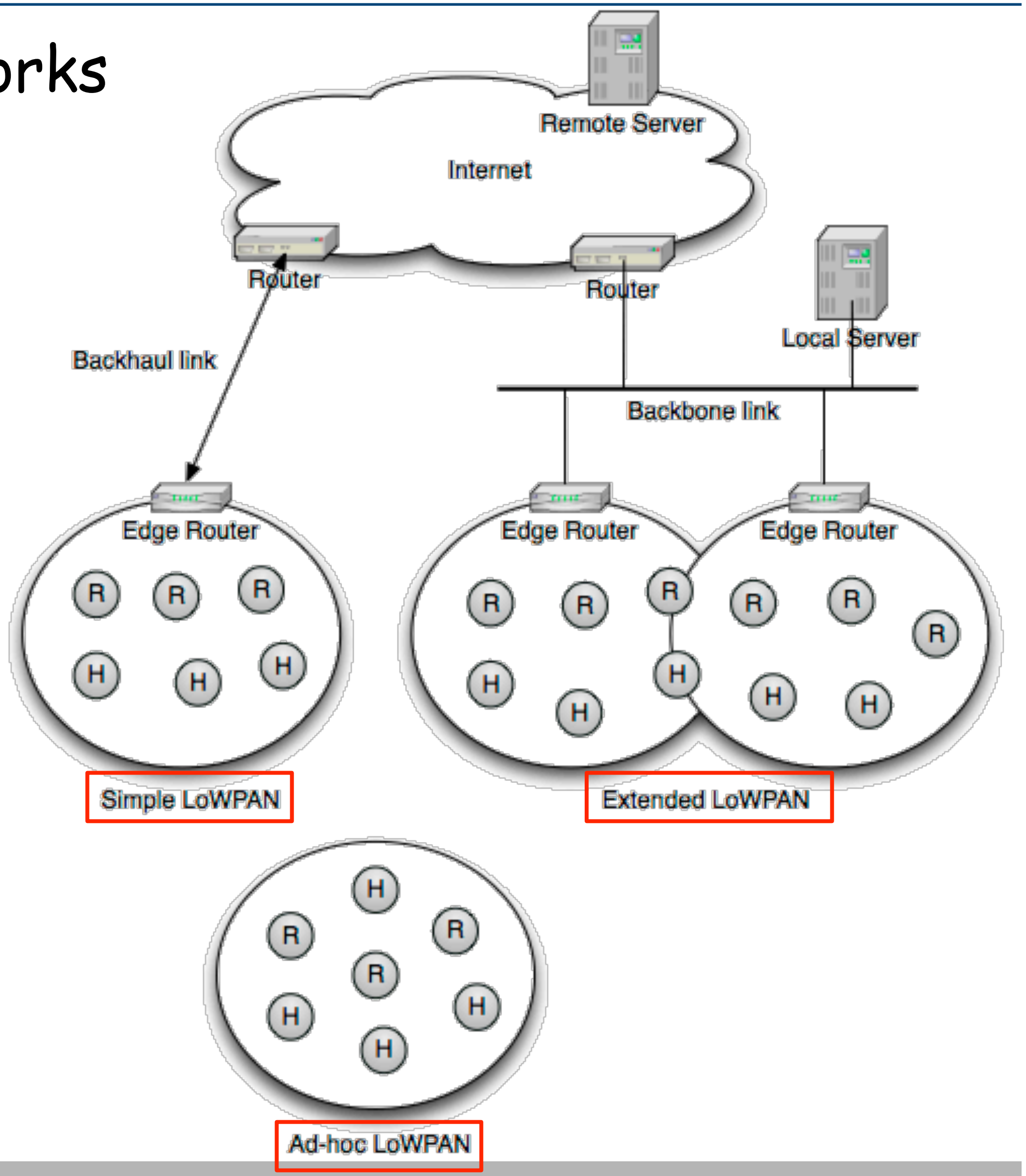


Protocol Stack



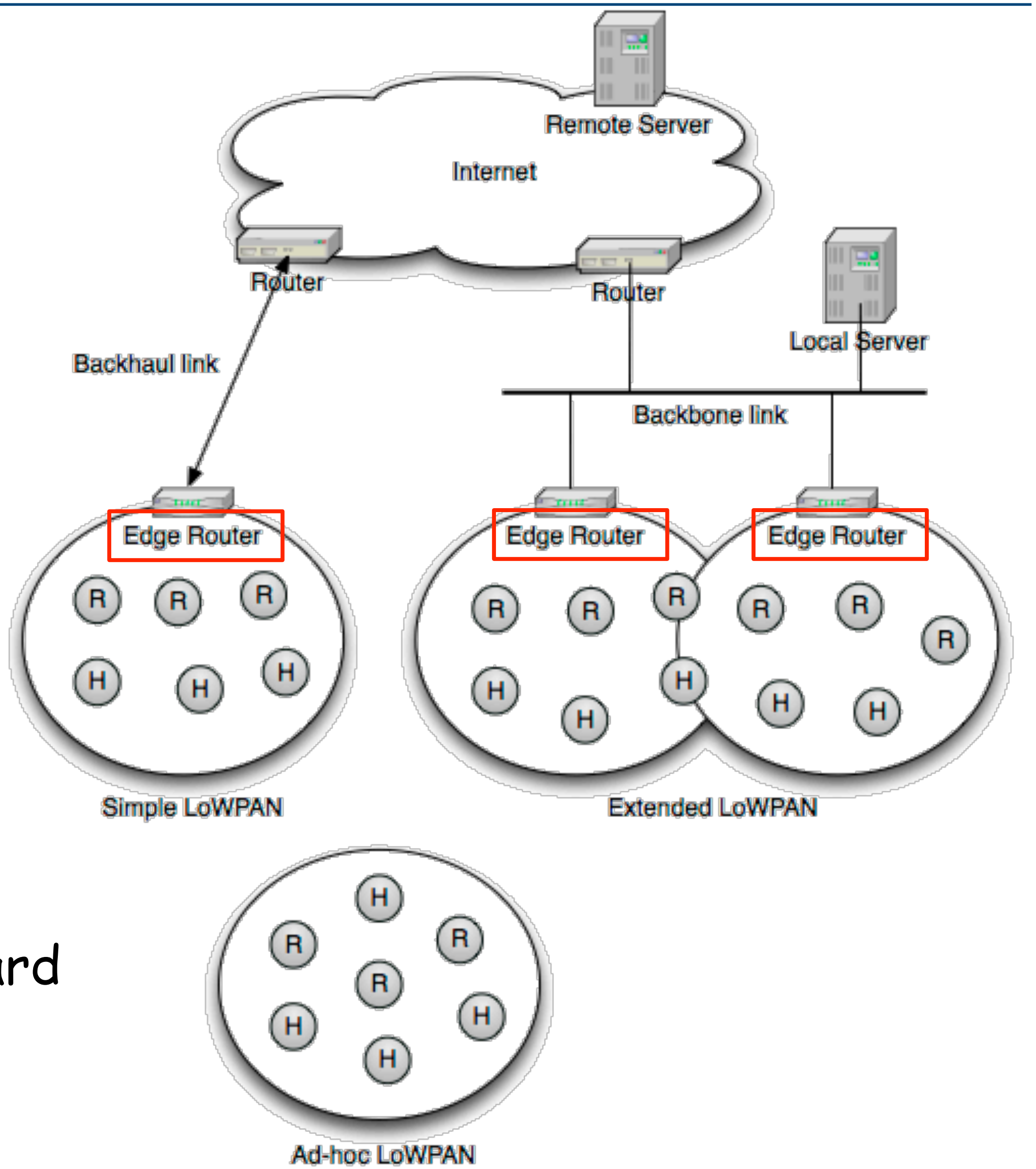
Architecture

- LoWPANs are stub networks
- Ad-hoc LoWPAN
  - No route outside the LoWPAN
- Simple LoWPAN
  - Single Edge Router
- Extended LoWPAN
  - Multiple Edge Routers with common backbone link



Architecture

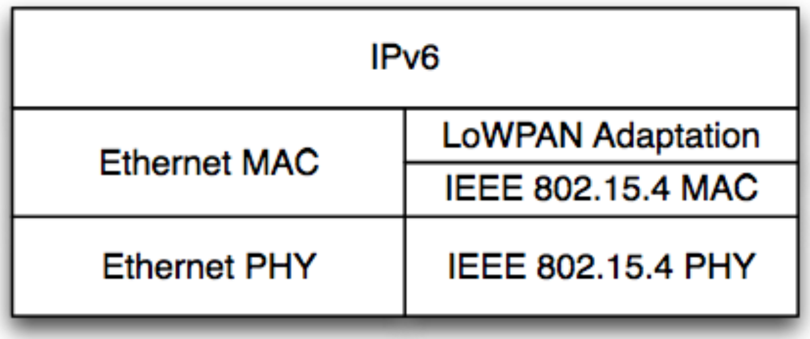
- Device types
  - H Host
  - R Router
  - ER Edge router



- Edge router
  - Runs special protocols
  - Simplifies operation
  - Shared database: Whiteboard

Architecture

- Internet Integration issues
  - Maximum transmission unit (1500 vs 127 bytes)
  - Application protocols
  - IPv4 interconnectivity
  - Firewalls and NATs
  - Security

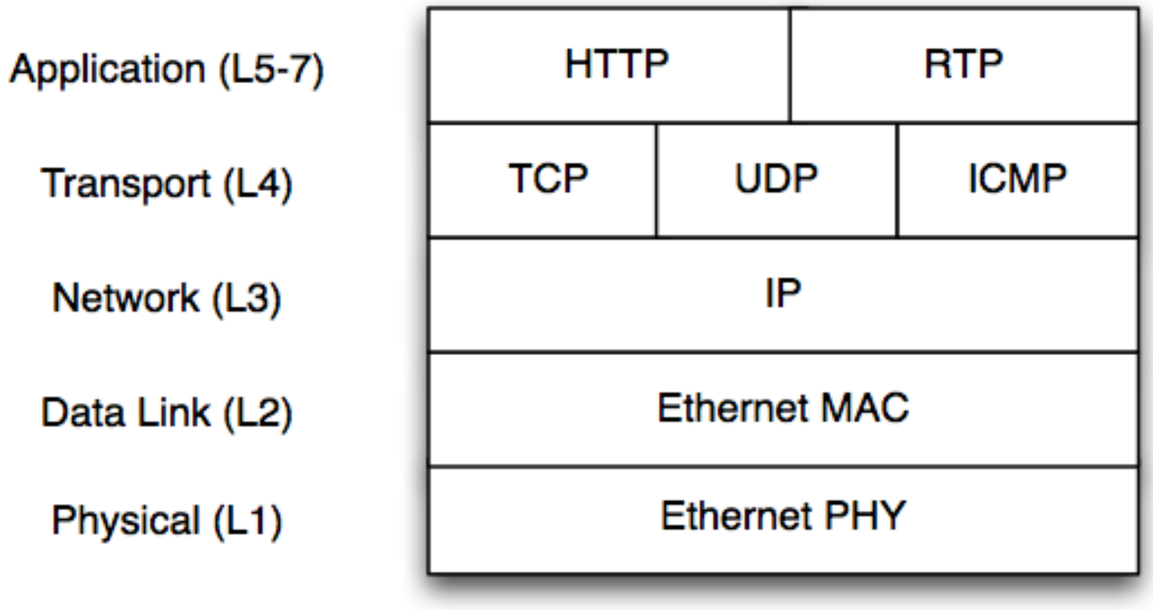


IPv6-LoWPAN Router Stack

Refresher

The Internet Architecture & Protocols

IP Protocol Stack



Internet Protocol v6

[RFC2460]

- IPv6 = the next generation Internet Protocol
  - Complete redesign of IP addressing
  - Hierarchical 128-bit address with decoupled host identifier
  - Stateless autoconfiguration
  - 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
    - 1400% annual growth in IPv6 traffic (2009)

IPv4 vs. IPv6 Addressing

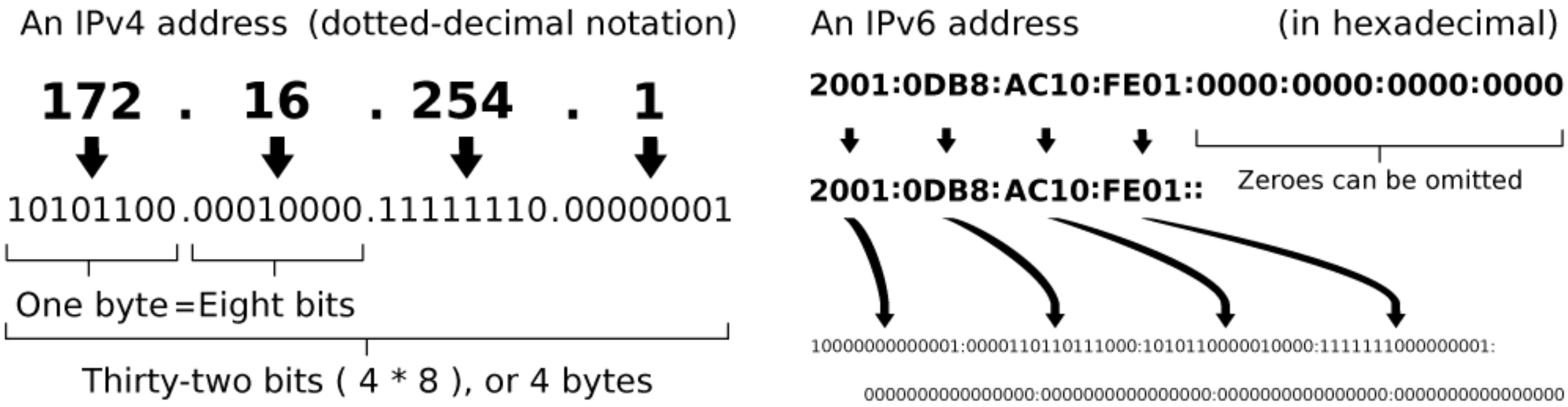
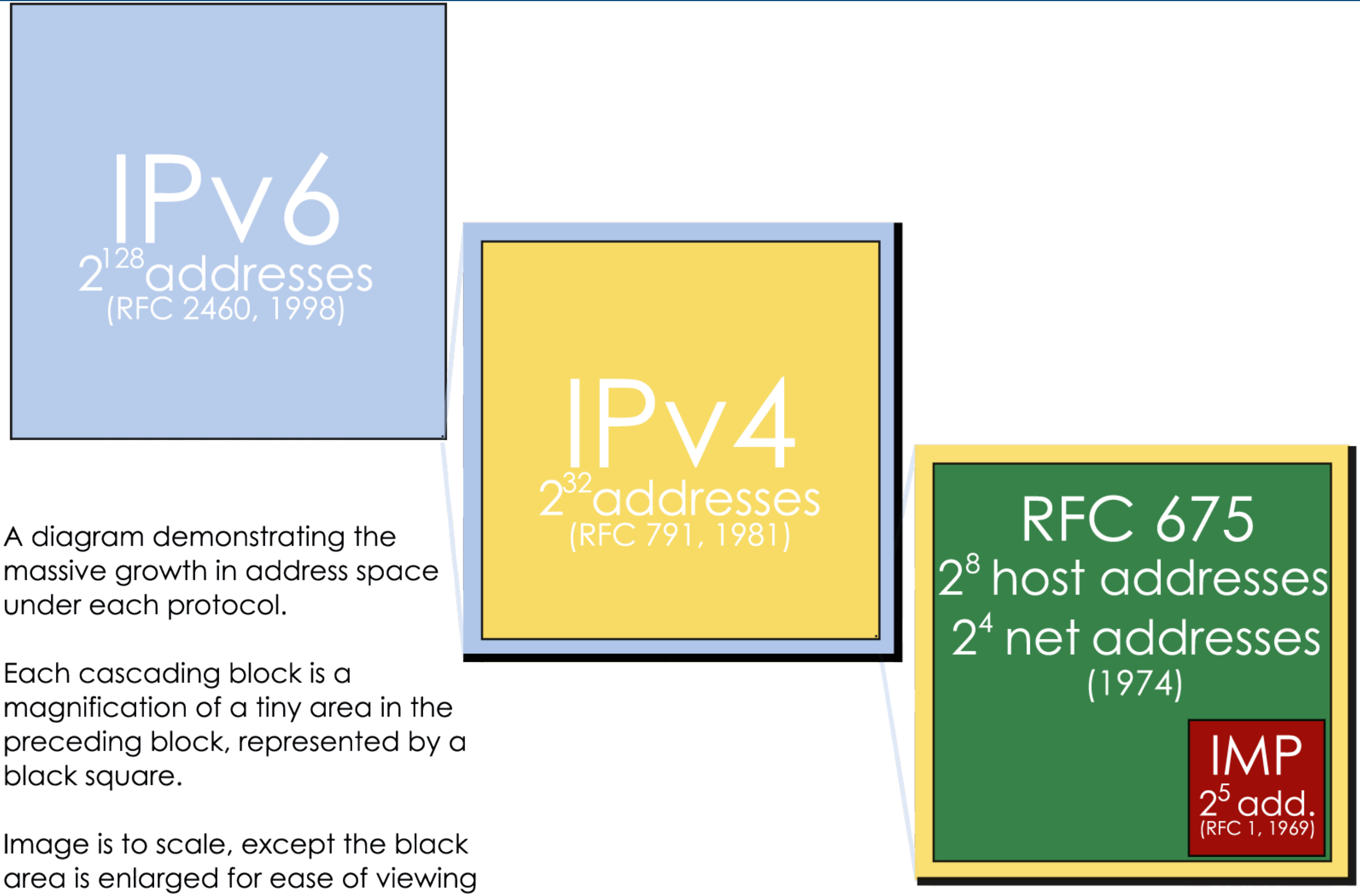


Image source: Indeterminant (Wikipedia) GFDL

Address Space Comparison



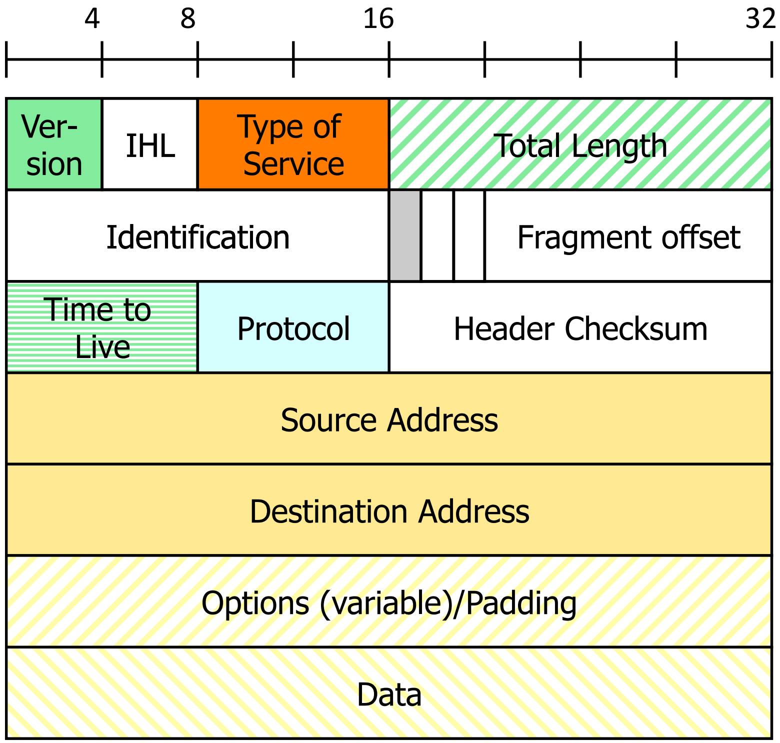
A diagram demonstrating the massive growth in address space under each protocol.

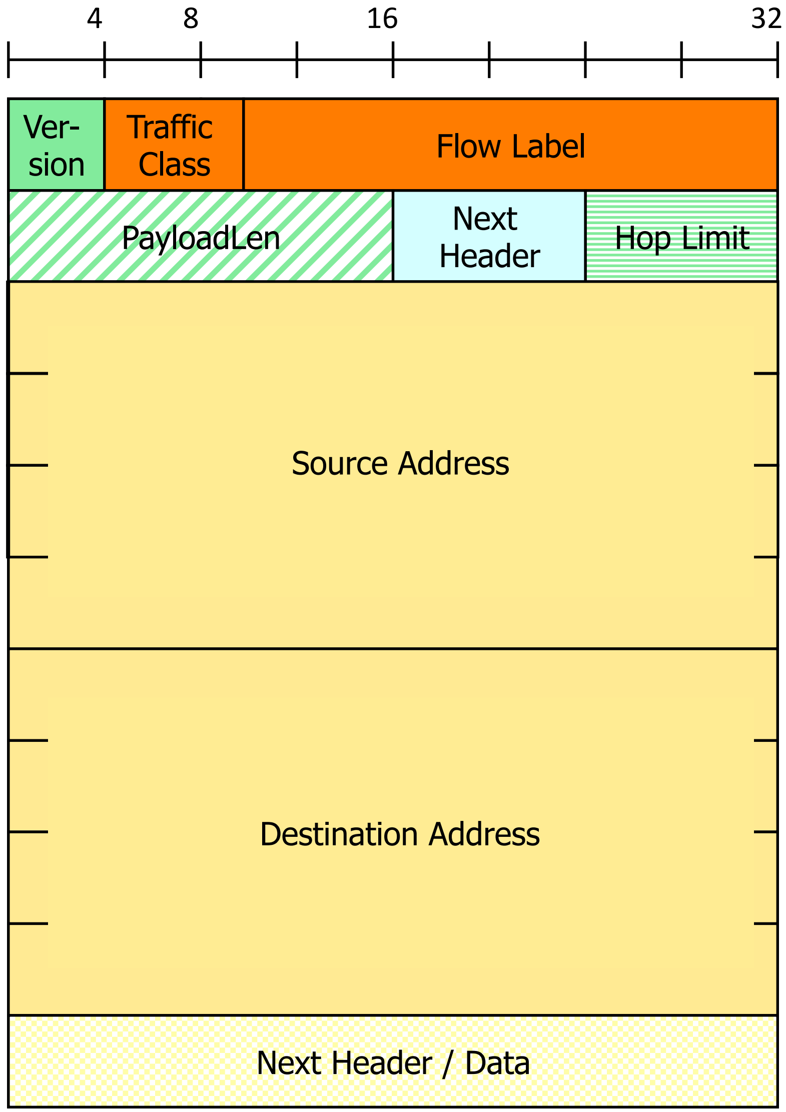
Each cascading block is a magnification of a tiny area in the preceding block, represented by a black square.

Image is to scale, except the black area is enlarged for ease of viewing

Image source: Smurrayinchester (Wikipedia) CC 3.0

IPv4 vs. IPv6: Header





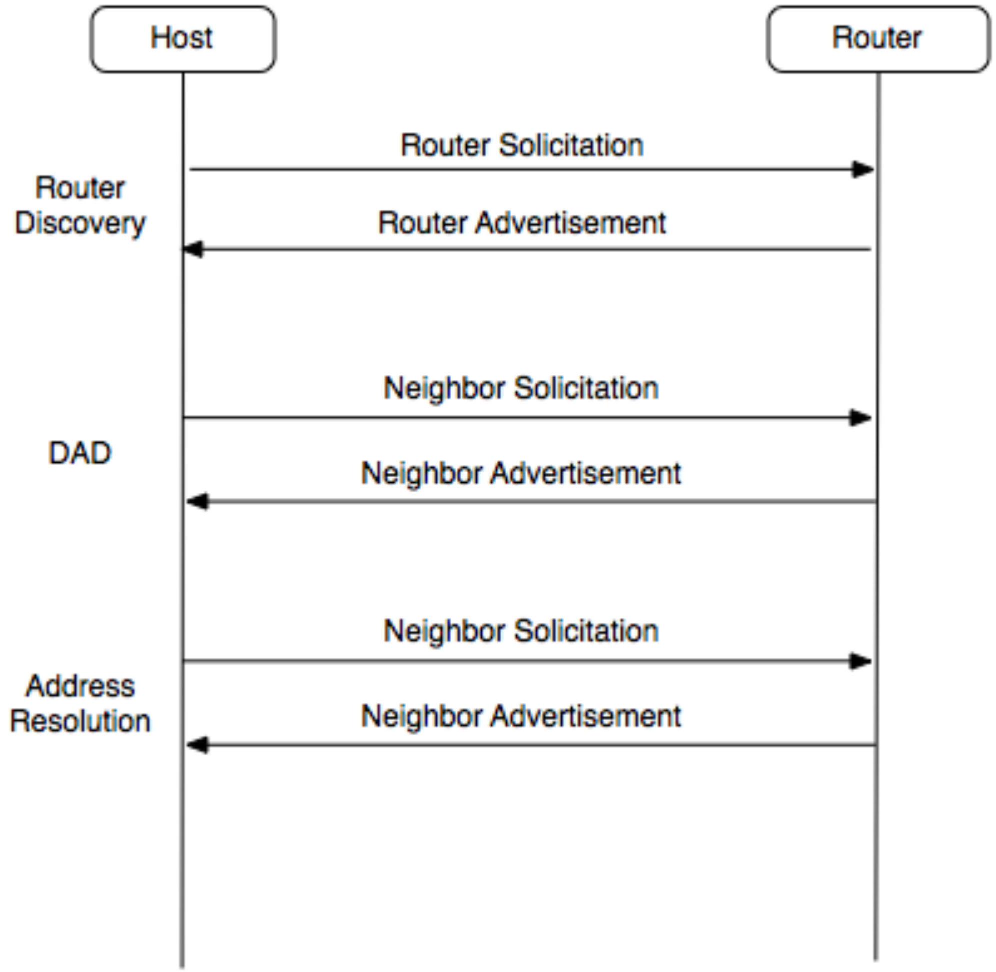
The IPv6 header is longer, but this is only caused by the longer addresses.

IPv6 Neighbor Discovery (ND)

[RFC4861]

- IPv6 is the format - ND is the brain
  - "One-hop routing protocol" defined in RFC4861
- Defines the interface between neighbors
- Finding Neighbors
  - Neighbor Solicitation (NS) / Neighbor Acknowledgement (NA)
- Finding Routers
  - Router Solicitation (RS) / Router Advertisement (RA)
- Address resolution using NS/NA
- Detecting Duplicate Addresses using NS/NA
- Neighbor Unreachability Detection using NS/NA
- DHCPv6 may be used in conjunction with ND

IPv6 Neighbor Discovery



ICMPv6

[RFC4443]

- The Internet Control Message Protocol (ICMPv6)
  - Used for control messaging between IPv6 nodes

- ICMPv6 Error Messages
  - Destination Unreachable Message
  - Packet Too Big Message
  - Time Exceeded Message
  - Parameter Problem Message

- ICMPv6 Informational Messages
  - Echo Request Message
  - Echo Reply Message

ICMPv6

[RFC4443]

```
The ICMPv6 messages have the following general format:

    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
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |     Type      |     Code      |          Checksum             |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                                                               |
   +                         Message Body                          +
   |                                                               |
```

The type field indicates the type of the message. Its value determines the format of the remaining data.

The code field depends on the message type. It is used to create an additional level of message granularity.

The checksum field is used to detect data corruption in the ICMPv6 message and parts of the IPv6 header.

TCP

[RFC793]

- The Transmission Control Protocol (TCP)
  - A reliable, ordered transport for a stream of bytes
  - TCP is connection oriented, forming a pairing between 2 hosts using a 3-way handshake
  - Positive ack windowing is used with flow control
  - Congestion control mechanism critical for the Internet

- TCP is not suitable for every application
  - Support for unicast communications only
  - Reacts badly to e.g. wireless packet loss
  - Not all protocols require total reliability
  - TCP connection not suitable for very short transactions

The TCP Header

[RFC793]

```
 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
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|          Source Port          |       Destination Port        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                        Sequence Number                        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Acknowledgment Number                      |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Data |           |U|A|P|R|S|F|                               |
| Offset| Reserved  |R|C|S|S|Y|I|            Window             |
|       |           |G|K|H|T|N|N|                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|           Checksum            |         Urgent Pointer        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Options                    |    Padding    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                             data                              |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

UDP

[RFC768]

- The User Datagram Protocol (UDP)
  - Used to deliver short messages over IP
  - Unreliable, connectionless protocol
  - Can be used with broadcast and multicast
  - Common in streaming and VoIP, DNS, and network tools

```
 0      7 8     15 16    23 24    31
+--------+--------+--------+--------+
|     Source      |   Destination   |
|      Port       |      Port       |
+--------+--------+--------+--------+
|                 |                 |
|     Length      |    Checksum     |
+--------+--------+--------+--------+
|
|          data octets ...
+---------------- ...
```

Refresher

Stateless Autoconfiguration

RFC4862 obsoletes RFC2462

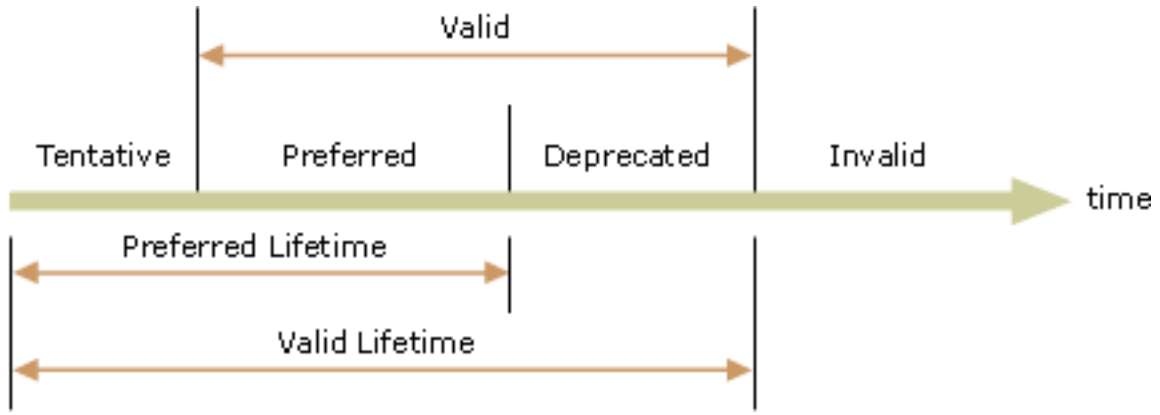
Design goals

- Manual configuration of individual machines before connecting them to the network should not be required.
  - Address autoconfiguration assumes that each interface can provide a unique identifier for that interface (i.e., an "interface token")
- Plug-and-play communication is achieved through the use of link-local addresses
  - Small sites should not need stateful servers
- A large site with multiple networks and routers should not require the presence of a stateful address configuration server.
- Address configuration should facilitate the graceful renumbering of a site's machines

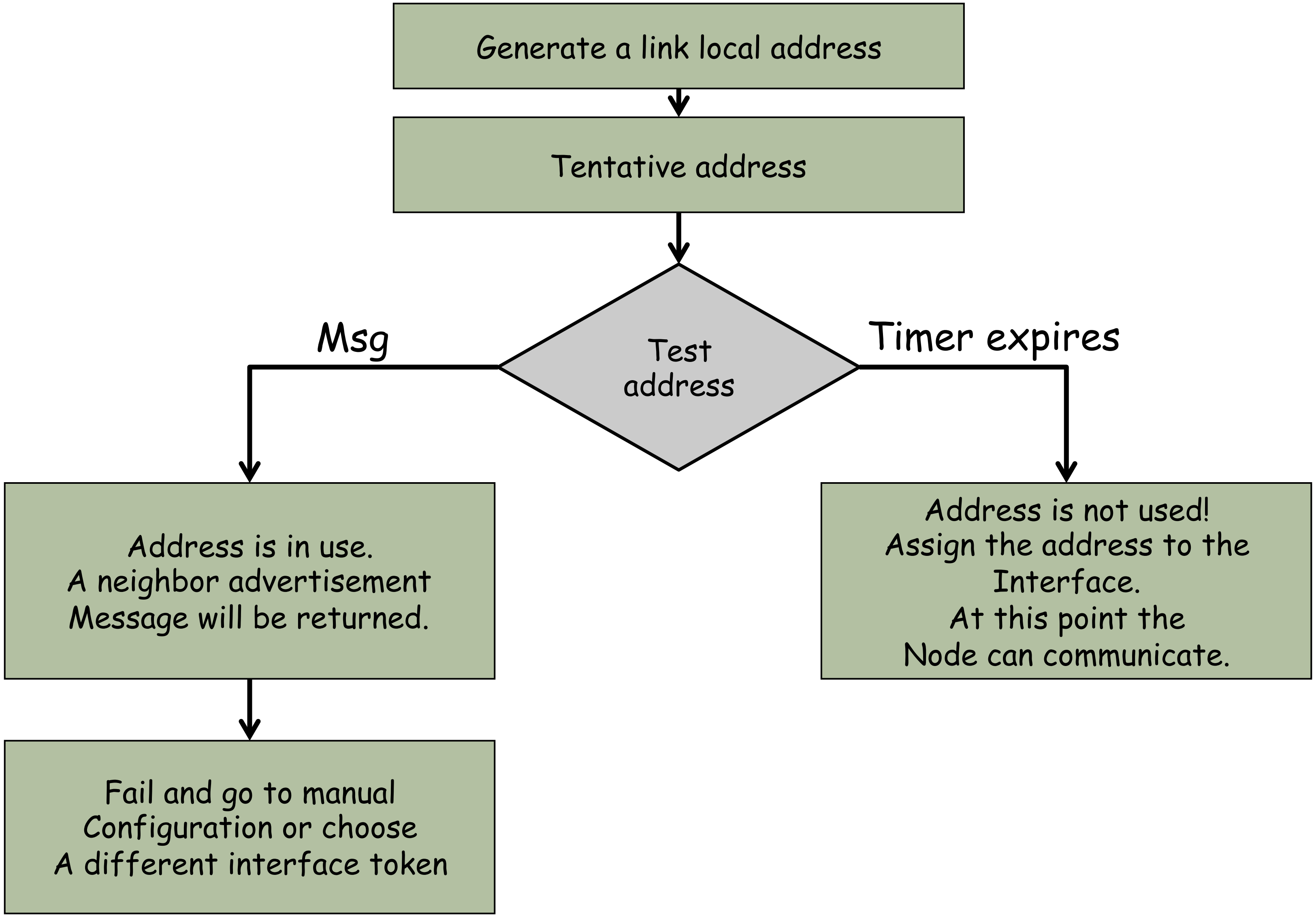
Design goals

- Tentative address
  - An address whose uniqueness on a link is being verified
  - An interface discards received packets addressed to a tentative address, but accepts Neighbor Discovery packets
- Preferred address
  - An address assigned to an interface whose use by upper-layer protocols is unrestricted.
- Deprecated address
  - An address assigned to an interface whose use is discouraged, but not forbidden
- Valid address
  - A preferred or deprecated address
- Invalid address
  - An address that is not assigned to any interface.
  - A valid address becomes invalid when its valid lifetime expires.

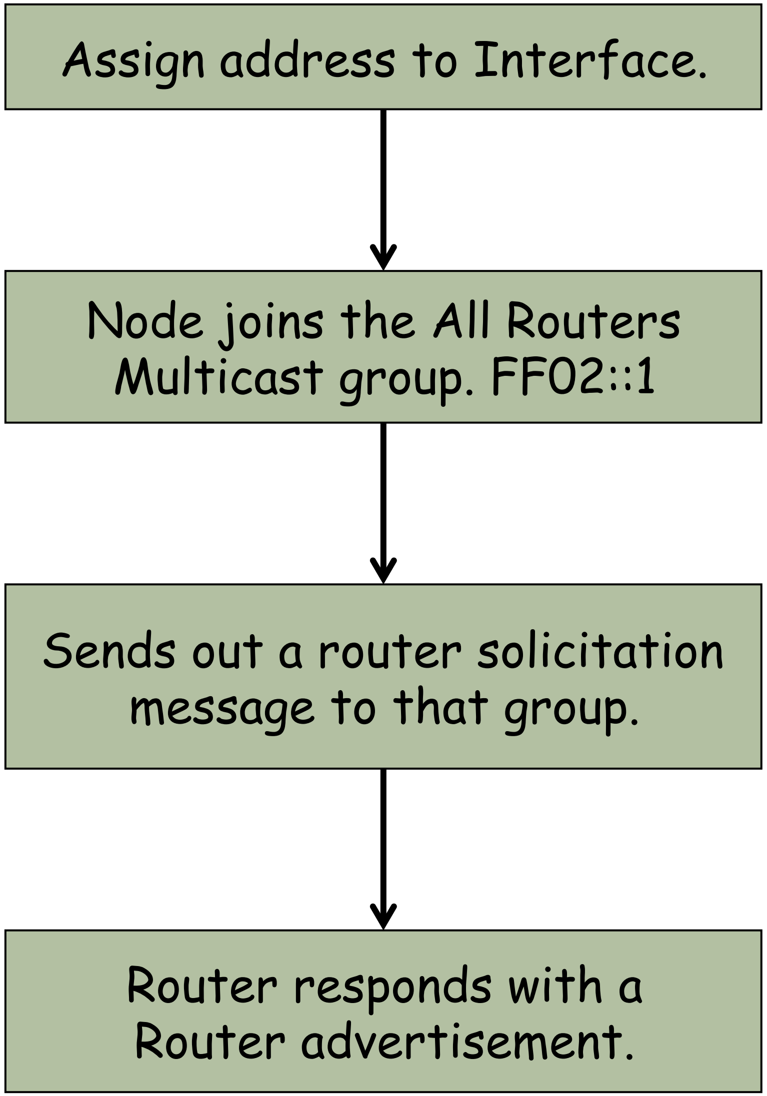
Design goals



Stateless Autoconfiguration



Stateless Autoconfiguration

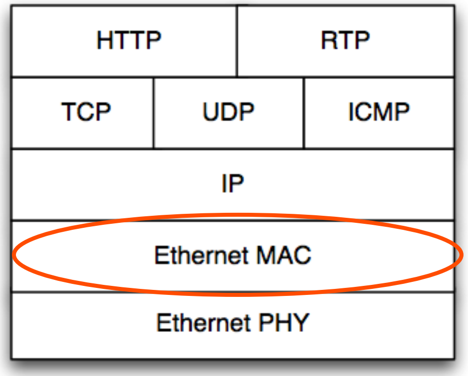


Refresher

Link Layer Technologies

The Link-Layer and IP

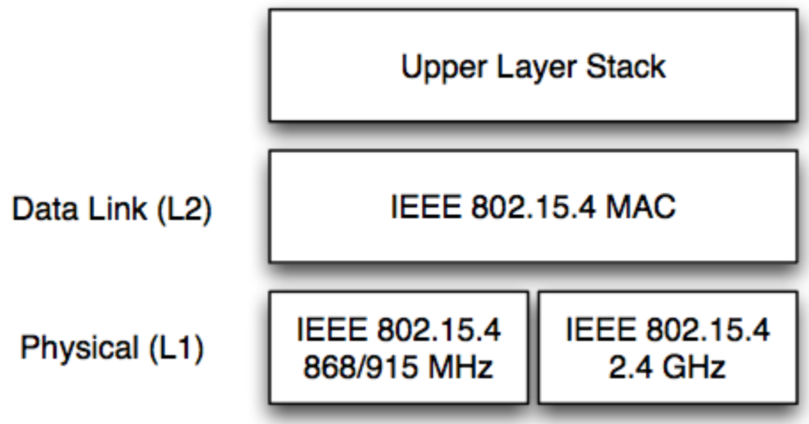
- The Internet Protocol interconnects heterogeneous links
- Key link-layer features to support IP
  - Framing
  - Addressing
  - Error checking
  - Length indication
  - Broadcast and unicast



- RFC3819 discusses IP subnetwork design
- 6LoWPAN enables IPv6 over very constrained links
  - Limited frame size and bandwidth
  - Wireless mesh topologies and sleeping nodes
  - No native multicast support

IEEE 802.15.4

- Important standard for home networking, industrial control and building automation
- Three PHY modes
  - 20 kbps at 868 MHz
  - 40 kbps at 915 MHz
  - 250 kbps at 2.4 GHz (DSSS)
- Beaconless mode
  - Simple CSMA algorithm
- Beacon mode with superframe
  - Hybrid TDMA-CSMA algorithm
- Up to 64k nodes with 16-bit addresses
- Extensions to the standard
  - IEEE 802.15.4a, 802.15.4e, 802.15.5



Other Link-Layers for 6LoWPAN

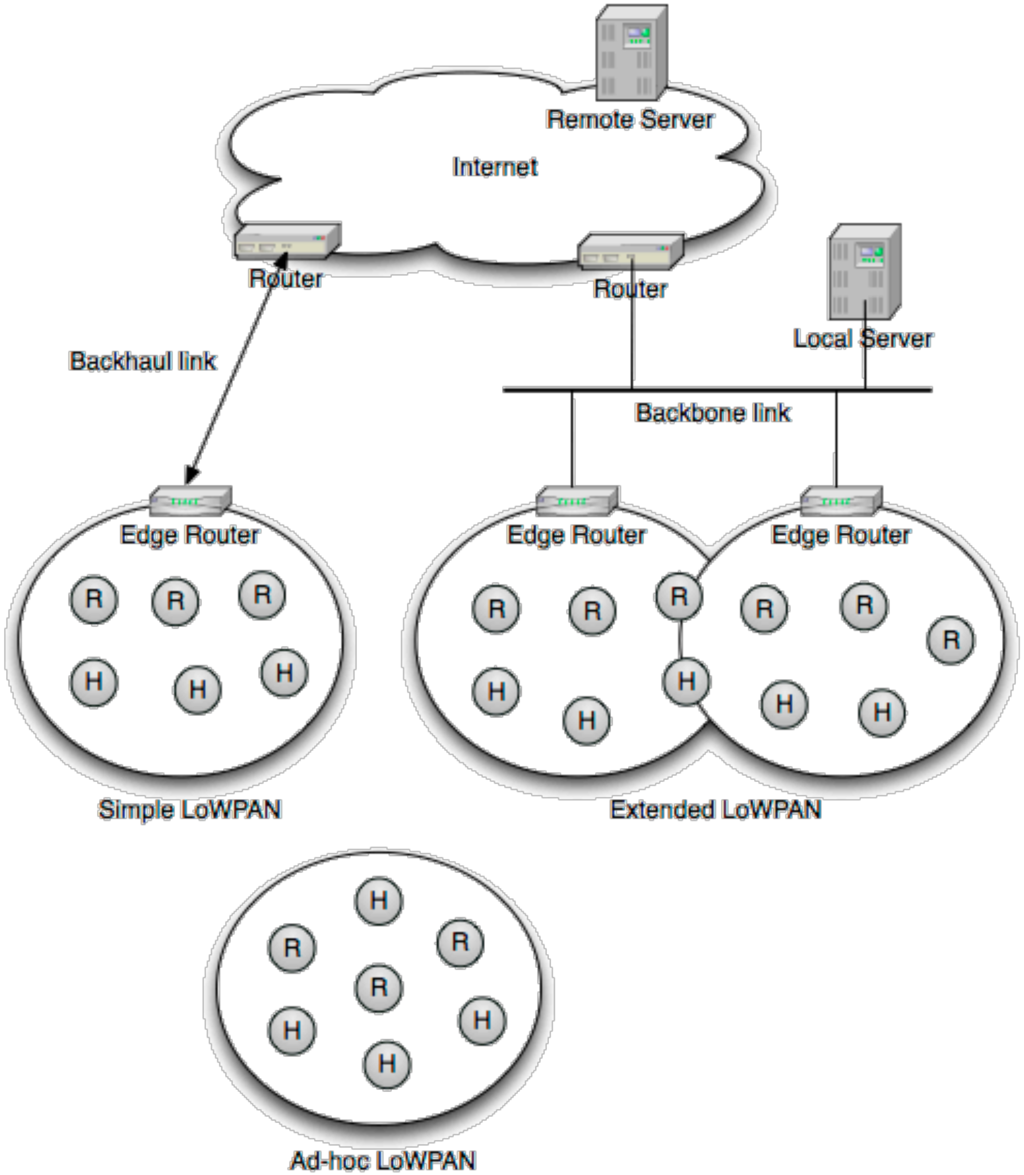
- Sub-GHz Industrial, Scientific and Medical band radios
  - Typically 10-50 kbps data rates, longer range than 2.4 GHz
  - Usually use CSMA-style medium access control
  - Example: CC1110 from Texas Instruments

- Power-Line Communications
  - Some PLC solutions behave like an 802.15.4 channel
  - Example: A technology from Watteco provides an 802.15.4 emulation mode, allowing the use of 6LoWPAN

- Z-Wave
  - A home-automation low-power radio technology

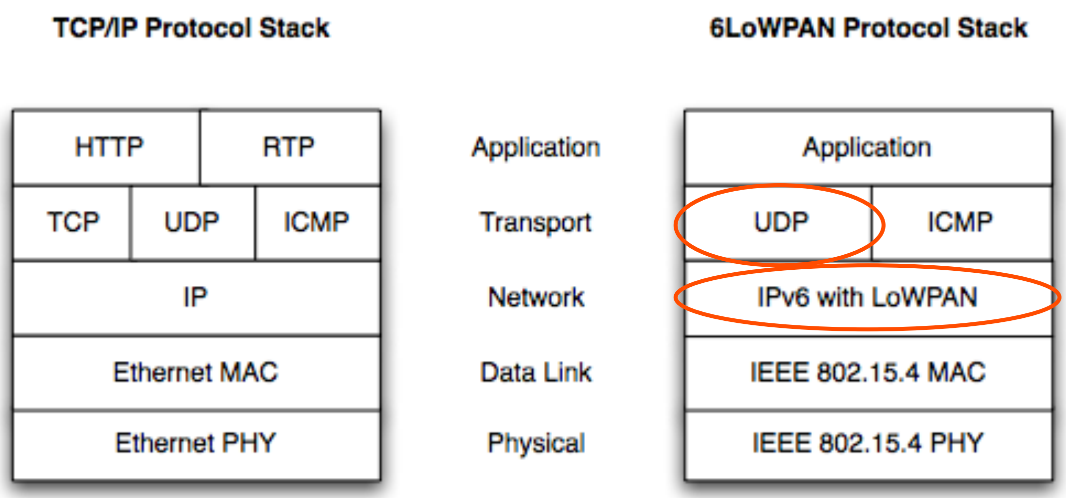
The 6LoWPAN Format

Architecture



The 6LoWPAN Format

- 6LoWPAN is an adaptation header format
  - Enables the use of IPv6 over low-power wireless links
  - IPv6 header compression
  - UDP header compression
- Format initially defined in RFC4944 updated by RFC6282



The 6LoWPAN Format

- 6LoWPAN makes use of IPv6 address compression

- RFC4944 Features:
  - Basic LoWPAN header format
  - HC1 (IPv6 header) and HC2 (UDP header) compression formats
  - Fragmentation & reassembly
  - Mesh header feature (depreciation planned)
  - Multicast mapping to 16-bit address space

- RFC6282 Features:
  - New HC (IPv6 header) and NHC (Next-header) compression
  - Support for global address compression (with contexts)
  - Support for IPv6 extension header compression
  - Support for UDP
  - Support for compact multicast address compression

The 6LoWPAN Format

Addressing

IPv6 Addressing

[RFC2373]

- 128-bit IPv6 address Interface ID (IID)

  64-bit prefix + 64-bit
- The 64-bit prefix is hierarchical
  - Identifies the network you are on and where it is globally
- The 64-bit IID identifies the network interface
  - Must be unique for that network
  - Typically is formed statelessly from the interface MAC address
    - Called Stateless Address Autoconfiguration (RFC4862)
- 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::)
  - Anycast addresses (special-purpose unicast address)

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 network
    - Link-local prefix indicated by header compression format
  - Compressing the IID
    - Elided for link-local communication
    - Compressed for multihop dst/src addresses
  - Compressing with a well-known "context"
  - Multicast addresses are compressed

6LoWPAN Addressing

- Forming addresses out of 16-bit short addresses
- Pseudo 48-bit address is formed in two steps:

  (1) 16_bit_PAN:16_zero_bits

  (2) 32_bits_as_specified_previously:16_bit_short_address

- The interface identifier is formed from this 48-bit address

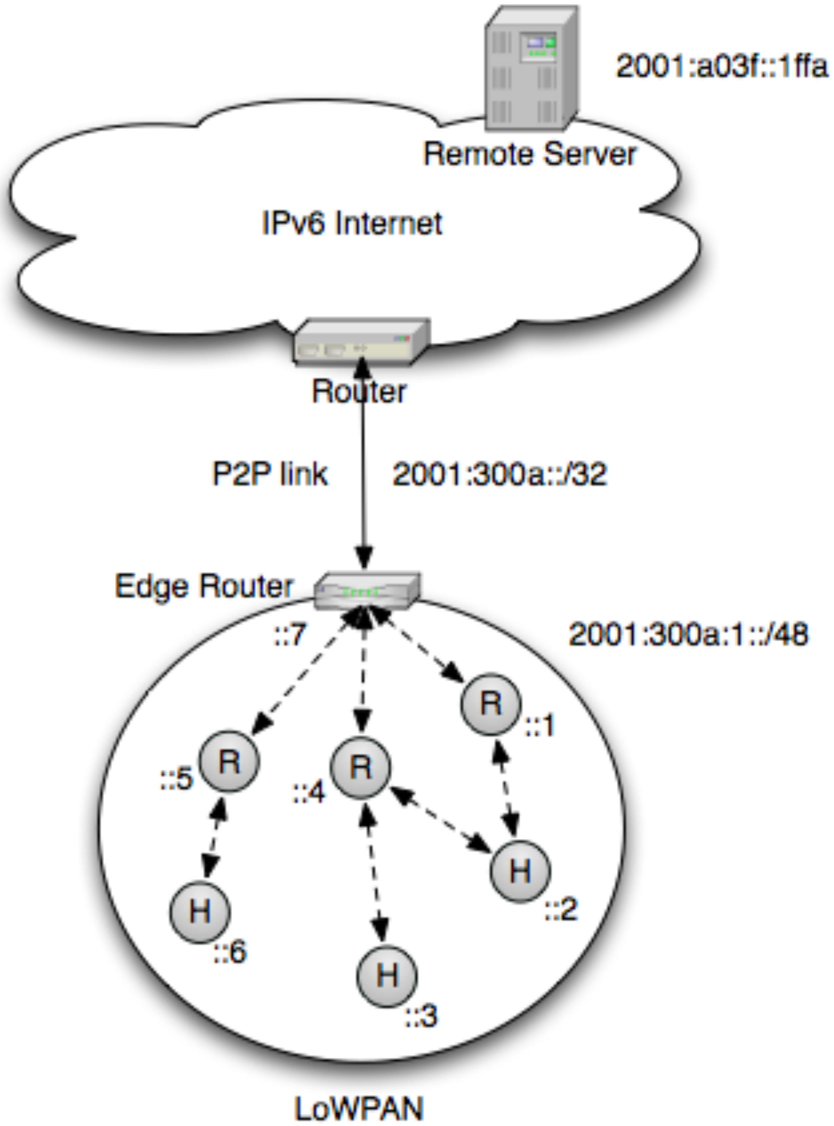
6LoWPAN Addressing

IPv6 Link Local Address

```
   The IPv6 link-local address [RFC4291] for an IEEE 802.15.4 interface
   is formed by appending the Interface Identifier, as defined above, to
   the prefix FE80::/64.


          10 bits            54 bits                  64 bits
        +----------+-----------------------+----------------------------+
        |1111111010|00       (zeros)     00|    Interface Identifier    |
        +----------+-----------------------+----------------------------+
          F   E   8  0
```

Addressing Example



The 6LoWPAN Format

Header compression

Header compression

- Large IPv6 datagram needs to be transmitted
- How to compress the header to save resources?

- Integrate Layer 2 and Layer 3 compression

UDP/IPv6 Headers

```
                 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
                +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
                |Version| Traffic Class |           Flow Label                  |
                +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
                |         Payload Length        |  Next Header  |   Hop Limit   |
                +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
                |                                                               |
                +                                                               +
                |                                                               |
                +                         Source Address                        +
                |                                                               |
 IPv6           +                                                               +
                |                                                               |
                +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+   48 Bytes
                |                                                               |
                +                                                               +
                |                                                               |
                +                      Destination Address                      +
                |                                                               |
                +                                                               +
                |                                                               |
                +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
                |          Source Port          |       Destination Port        |
 UDP            +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
                |            Length             |           Checksum            |
                +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 Payload ------>|          UDP Payload         ...
                +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Encoding of IPv6 Header Fields

[RFC4944]

- Encode different combinations with “HC1 encoding”

```
                     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
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| HC1 encoding  |     Non-Compressed fields follow...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+

          LOWPAN_HC1 (common compressed header encoding)
```

```
The address fields encoded by "HC1 encoding" are interpreted as follows:
      PI:  Prefix carried in-line
      PC:  Prefix compressed (link-local prefix assumed)
      II:  Interface identifier carried in-line
      IC:  Interface identifier elided -> derivable from link-layer address
```

Encoding of IPv6 Header Fields

[RFC4944]

- Encode different combinations with "HC1 encoding"

```
                     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
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|S A|D A|T|N H|H|     Non-Compressed fields follow...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

```
SA   Source address                (bits 0 and 1)
DA   Destination address           (bits 2 and 3)
T    Traffic class and Flow Label  (bit 4)
NH   Next header                   (bits 5 and 6)
H    HC2 encoding                  (bit 7)
```

LoWPAN Adaptation Layer and Frame Format

These examples show typical header stacks that may be used in a LoWPAN network.

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 fragmentation:

```
+-----------+-------------+--------------+------------+---------+
| Frag Type | Frag Header | HC1 Dispatch | HC1 Header | Payload |
+-----------+-------------+--------------+------------+---------+
```

LoWPAN Adaptation Layer and Frame Format

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 |
+-------+-------+-------+-------+---------+---------+---------+
```

A LoWPAN encapsulated LOWPAN_HC1 compressed IPv6 datagram that requires both mesh addressing and a broadcast header to support mesh broadcast/multicast:

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

Dispatch Type and Header

The dispatch type is defined by a zero bit as the first bit and a one bit as the second bit. The dispatch type and header are shown here:

```
                    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
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|0 1| Dispatch  | type-specific header
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Dispatch 6-bit selector: Identifies the type of header immediately following the Dispatch Header.

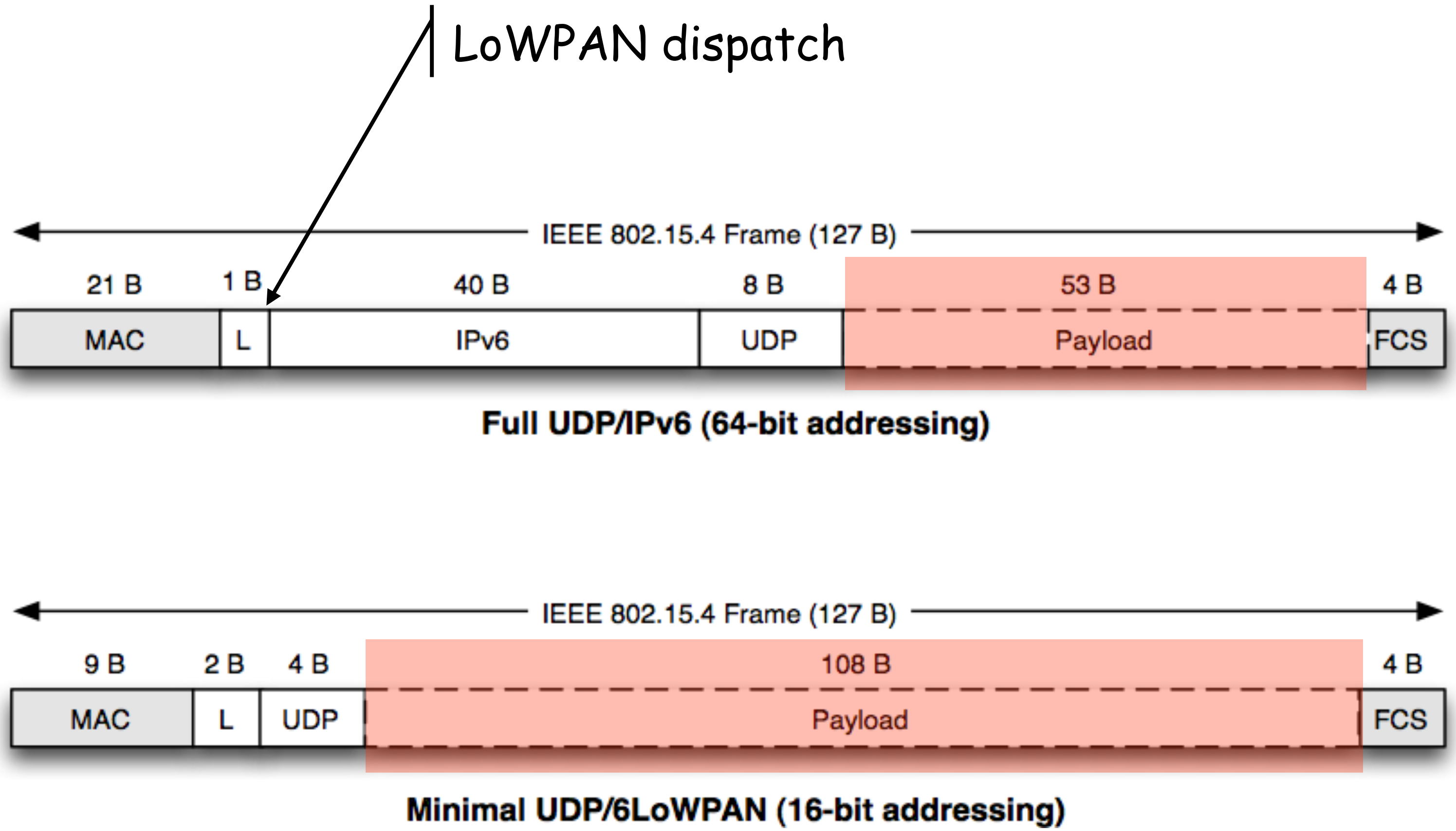
type-specific header: A header determined by the Dispatch Header.

The dispatch value may be treated as an unstructured namespace. Only a few symbols are required to represent current LoWPAN functionality. Although some additional savings could be achieved by encoding additional functionality into the dispatch byte, these measures would tend to constrain the ability to address future alternatives.

Dispatch Value Bit Pattern

Pattern		Header Type		
00	xxxxxx	NALP	-	Not a LoWPAN frame
01	000001	IPv6	-	Uncompressed IPv6 Addresses
01	000010	LOWPAN_HC1	-	LOWPAN_HC1 compressed IPv6
01	000011	reserved	-	Reserved for future use
...		reserved	-	Reserved for future use
01	001111	reserved	-	Reserved for future use
01	010000	LOWPAN_BC0	-	LOWPAN_BC0 broadcast
01	010001	reserved	-	Reserved for future use
...		reserved	-	Reserved for future use
01	111110	reserved	-	Reserved for future use
01	111111	ESC	-	Additional Dispatch byte follows
10	xxxxxx	MESH	-	Mesh Header
11	000xxx	FRAG1	-	Fragmentation Header (first)
11	001000	reserved	-	Reserved for future use
...		reserved	-	Reserved for future use
11	011111	reserved	-	Reserved for future use
11	100xxx	FRAGN	-	Fragmentation Header (subsequent)
11	101000	reserved	-	Reserved for future use
...		reserved	-	Reserved for future use
11	111111	reserved	-	Reserved for future use

Header Comparison



LoWPAN UDP/IPv6 Headers

[RFC6282]

LoWPAN IPv6 UDP

```
 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
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   Dispatch with LOWPAN_IPHC   |   LOWPAN_NHC  |  Src  |  Dst  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|          UDP Checksum         |          UDP Payload      ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

6 Bytes

Payload

IP Header Compression (IPHC)

[RFC6282]

```
LOWPAN_IPHC Header

+-------------------------------------+----------------------------
| Dispatch + LOWPAN_IPHC (2-3 octets) | In-line IPv6 Header Fields
+-------------------------------------+----------------------------
```

- In the best case, the LOWPAN_IPHC can compress the IPv6 header down to two octets
  - the dispatch octet and
  - the LOWPAN_IPHC encoding with link-local communication
- When routing over multiple IP hops, LOWPAN_IPHC can compress the IPv6 header down to 7 octets
  - 1 octet dispatch
  - 1 octet LOWPAN_IPHC
  - 1 octet Hop Limit
  - 2 octet Source Address
  - 2 octet Destination Address

IP Header Compression (IPHC)

[RFC6282]

LOWPAN_IPHC Encoding

```
 0   1   2   3   4   5   6   7   8   9   0   1   2   3   4   5
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
| 0 | 1 | 1 |  TF   |NH | HLIM  |CID|SAC|  SAM  | M |DAC|  DAM  |
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
```

```
TF   = Traffic Class, Flow Label
NH   = Next Header Flag
HLIM = Hop Limit
CID  = Context Identifier Extension
SAC  = Source Address Compression
SAM  = Source Address Mode
M    = Multicast Compression
DAC  = Destination Address Compression
DAM  = Destination Address Mode
```

IP Header Compression (IPHC)

IPv6 Extension Header Encoding

```
   0   1   2   3   4   5   6   7
 +---+---+---+---+---+---+---+---+
 | 1 | 1 | 1 | 0 |    EID    |NH |
 +---+---+---+---+---+---+---+---+
```

EID: IPv6 Extension Header ID
NH: Next Header

UDP Header Compression

[RFC6282]

NHC Format

```
+----------------+--------------------------
| var-len NHC ID | compressed next header...
+----------------+--------------------------
```

UDP NHC Encoding

```
  0   1   2   3   4   5   6   7
+---+---+---+---+---+---+---+---+
| 1 | 1 | 1 | 1 | 0 | C |   P   |
+---+---+---+---+---+---+---+---+
```

C = Checksum Compression
P = UDP Port Compression

The 6LoWPAN Format

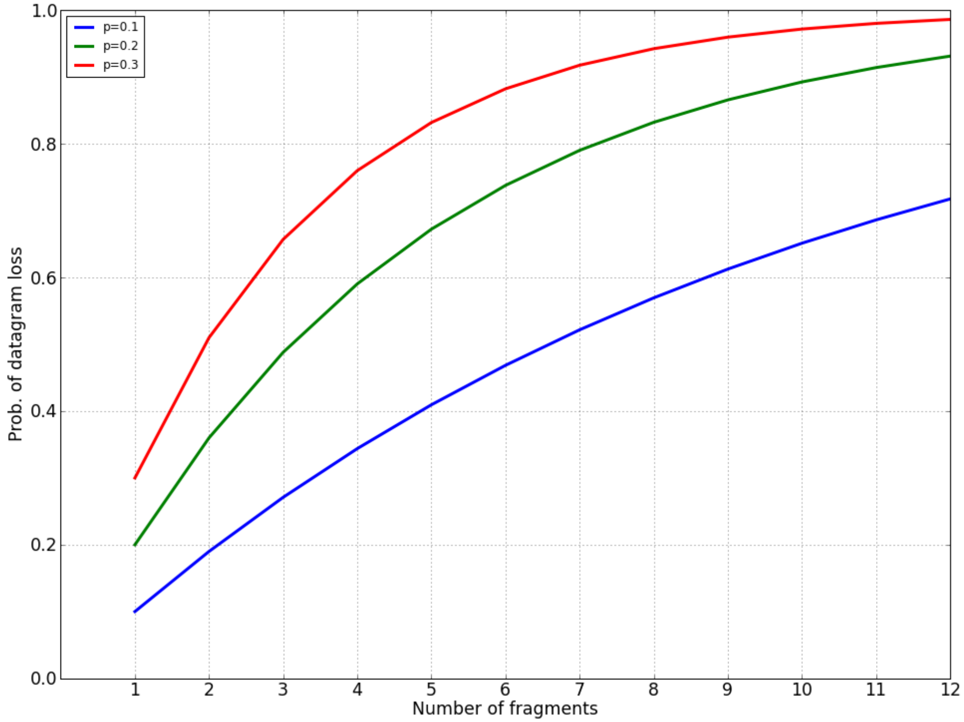
Fragmentation

Fragmentation

- IPv6 requires underlying links to support Minimum Transmission Units (MTUs) of at least 1280 bytes
- IEEE 802.15.4 leaves approximately 80-100 bytes of payload!
- RFC4944 defines fragmentation and reassembly of IPv6
- The performance of large IPv6 packets fragmented over low-power wireless mesh networks is poor!
  - Lost fragments cause whole packet to be retransmitted
  - Low-bandwidth and delay of the wireless channel
  - 6LoWPAN application protocols should avoid fragmentation
  - Compression should be used on existing IP application protocols when used over 6LoWPAN if possible

Fragmentation

- Impact of fragmentation in LoWPANs
- Assumptions
  - p   Uncorrelated packet loss probability
  - n   Number of fragments
- Probability of datagram loss: $1-(1-p)^n$



Fragmentation

Encodes the size of the entire IP packet before link-layer fragmentation

Initial 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 0 0 0|    datagram_size    |         datagram_tag          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Identification of fragments of the same IPv6 datagram

Following Fragments

```
 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|
+-+-+-+-+-+-+-+-+
```

Bootstrapping

6LoWPAN Setup & Operation

- Autoconfiguration is important in embedded networks

- In order for a 6LoWPAN network to start functioning:
  1. Link-layer connectivity between nodes (commissioning)
  2. Network layer address configuration, discovery of neighbors, registrations (bootstrapping)
  3. Routing algorithm sets up paths (route initialization)
  4. Continuous maintenance of 1-3

Link-layer Commissioning

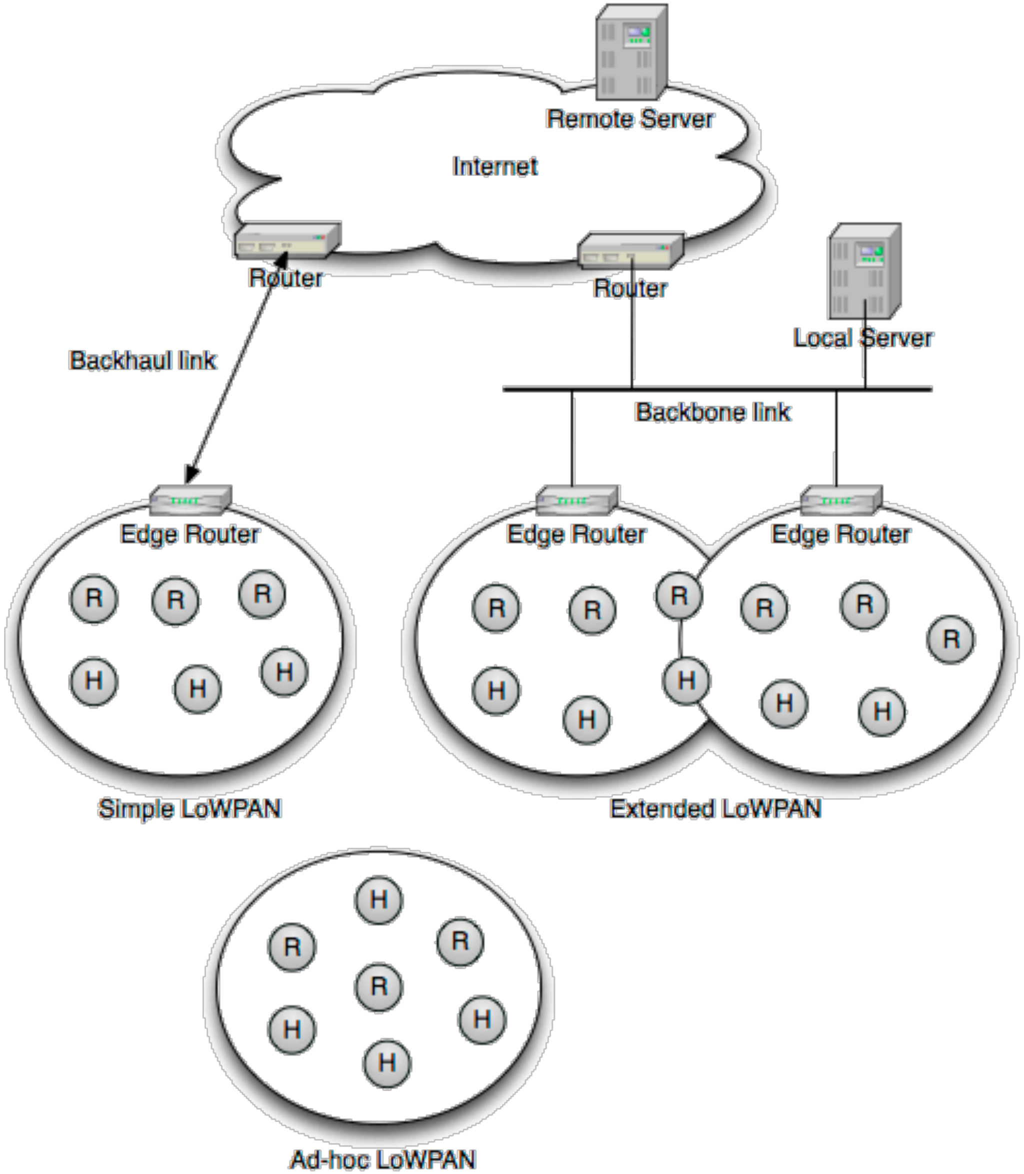
- In order for nodes to communicate with each other, they need to have compatible physical and link-layer settings.

- Example IEEE 802.15.4 settings:
  - Channel, modulation, data-rate (Channels 11-26 at 2.4 GHz)
    - Usually a default channel is used, and channels are scanned to find a router for use by Neighbor Discovery
  - Addressing mode (64-bit or 16-bit)
    - Typically 64-bit is a default and 16-bit used if address available
  - MAC mode (beaconless or super-frame)
    - Beaconless mode is easiest for commissioning (no settings needed)
  - Security (on or off, encryption key)
    - In order to perform secure commissioning a default key should already be installed in the nodes

6LoWPAN Neighbor Discovery

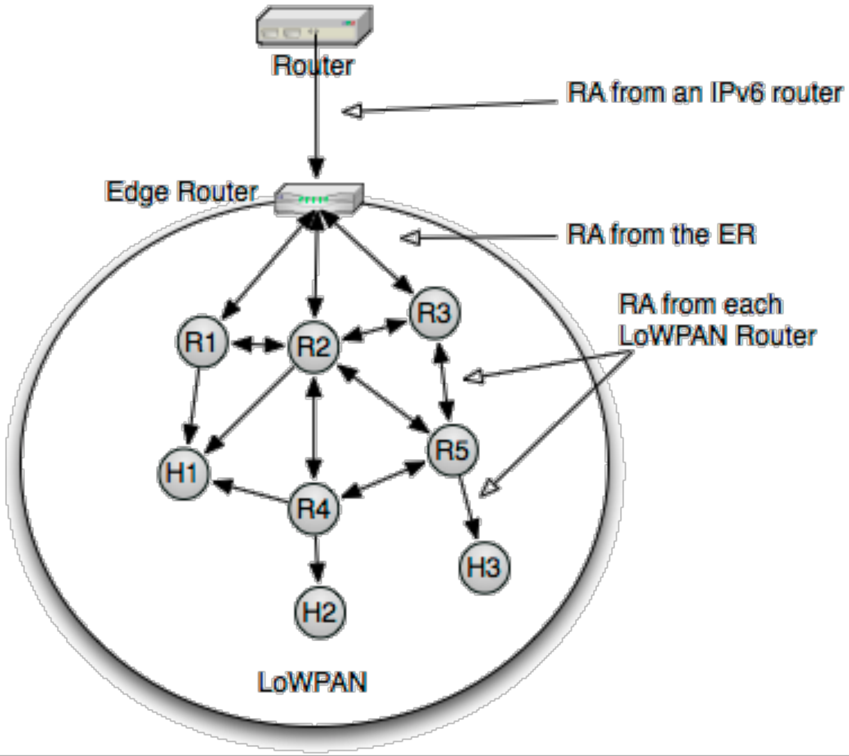
- Standard ND for IPv6 is not appropriate for 6LoWPAN:
  - Assumption of a single link for an IPv6 subnet prefix
  - Assumption that nodes are always on
  - Heavy use of multicast traffic (broadcast/flood in 6LoWPAN)
  - No efficient multihop support over e.g. 802.15.4
- 6LoWPAN Neighbor Discovery provides:
  - An appropriate link and subnet model for low-power wireless
  - Minimized node-initiated control traffic
  - Node Registration (NR) and Confirmation (NC)
  - Duplicate Address Detection (DAD) and recovery
  - Support for extended Edge Router infrastructures
- ND for 6LoWPAN has been specified in RFC6775

Architecture



Prefix Dissemination

- In normal IPv6 networks RAs are sent to a link based on the information (prefix etc.) configured for that router interface
- In ND for 6LoWPAN RAs are also used to automatically disseminate router information across multiple hops



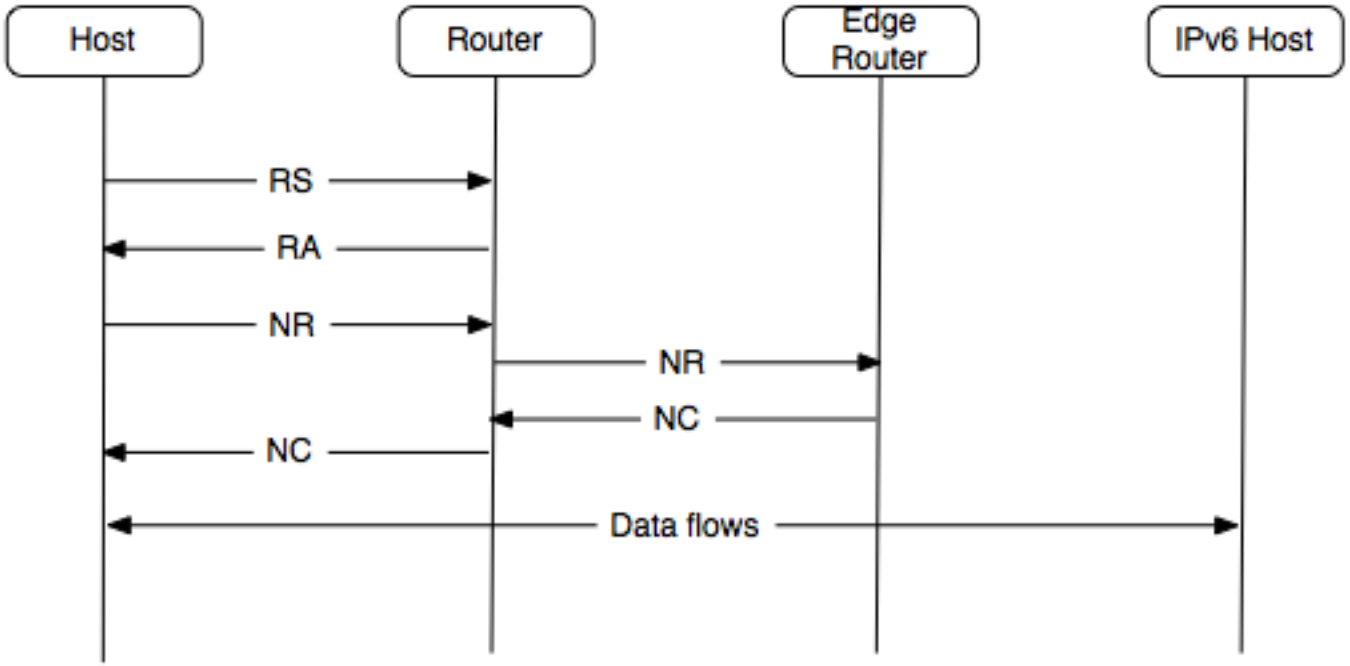
Node Registration

- 6LoWPAN-ND Optimizes only the **host-router** interface
  - RFC4861 = signaling between all neighbors (distributed)
- Nodes register with their neighboring routers
  - Exchange of NR/NC messages
  - Binding table of registered nodes kept by the router
- Node registration exchange enables
  - Host/router unreachability detection
  - Address resolution (a priori)
  - Duplicate address detection
- Registrations are soft bindings
  - Periodically refreshed with a new NR message

NR/NC Format

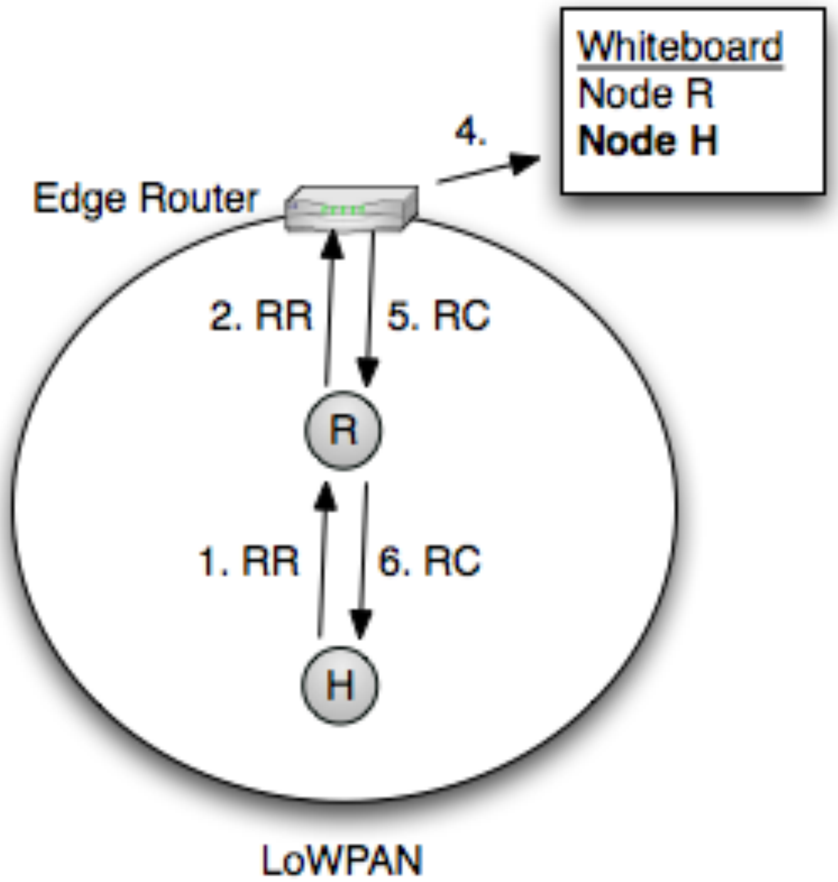
```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| Type (NR)/(NC)|     Code      |          Checksum             |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|      TID      |     Status    |P|_____________________________|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|        Binding Lifetime       |     Advertising Interval      |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                  Owner Interface Identifier                   +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                          Owner Nonce                          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   Registration option(s)...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Typical 6LoWPAN-ND Exchange



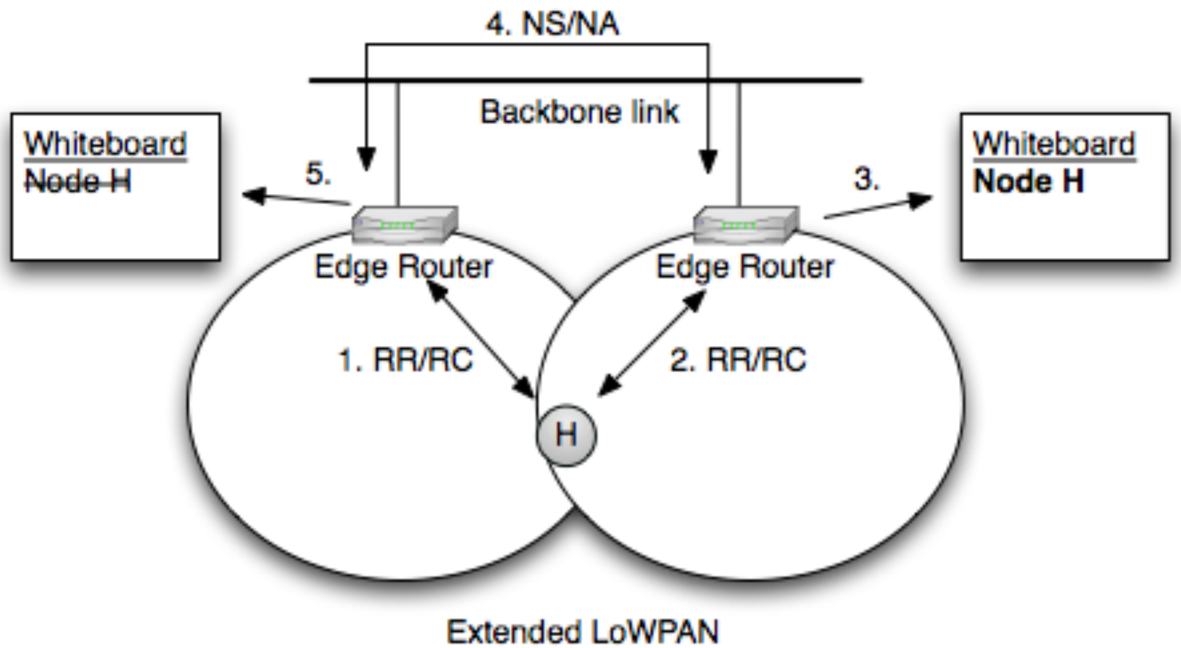
The Whiteboard

- The whiteboard is used in the LoWPAN for:
  - Duplicate address detection for the LoWPAN (= prefix)
  - Dealing with mobility (Extended LoWPANs)
  - Short address generation
  - Locating nodes



Extended LoWPANs

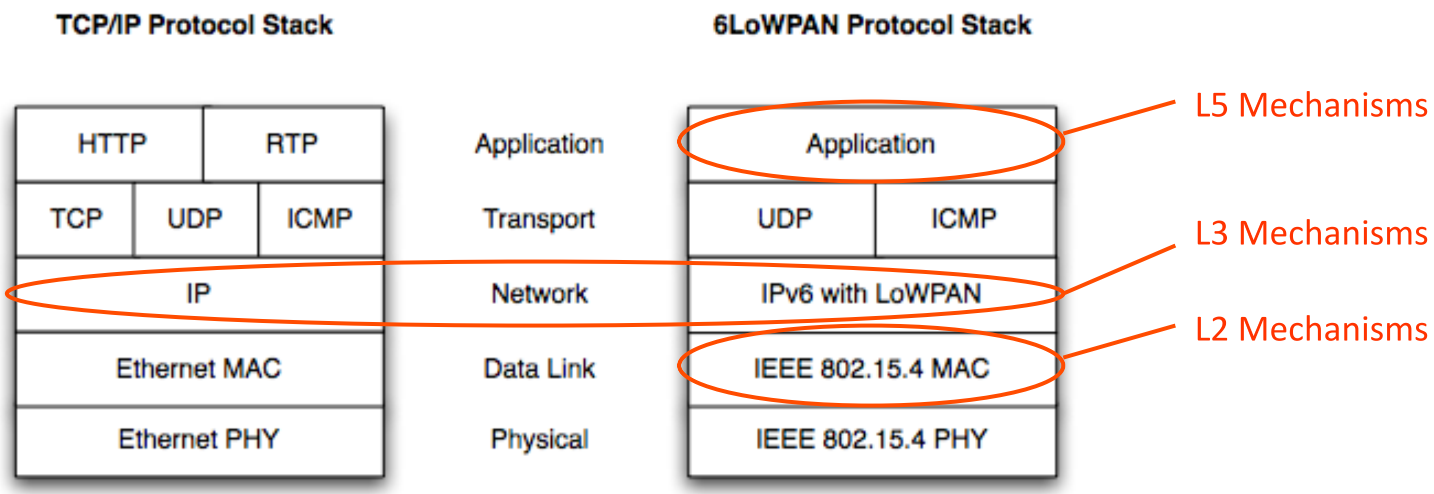
- Extended LoWPANs consist of two or more LoWPANs:
  - Which share the same IPv6 prefix
  - Which are connected together by a backbone link
- Whiteboards are synchronized over the backbone link



Security

Security for 6LoWPAN

- Security is important in wireless embedded networks
  - Wireless radios are easily overheard
  - Autonomous devices with limited processing power
- A system usually has three main security goals
  - Confidentiality
  - Integrity
  - Availability
- See the threat model for Internet security in RFC3552



Layer-2 Mechanisms

- Internet security is usually thought of as end-to-end
- In wireless networks the channel itself is very vulnerable
  - The channel is easy to overhear
  - Nodes and packets are easy to spoof
- The goals of security at the data-link layer
  - Protect the wireless network against attackers
  - Increase robustness against attacks
- IEEE 802.15.4 provides built-in encryption
  - Based on the 128-bit Advanced Encryption Standard (AES)
  - Counter with CBC-MAC mode (CCM)
    - Provides both encryption and an integrity check
  - Most chips include an AES-128 hardware engine

Layer-3 Mechanisms

- End-to-end security can be provided by IP
  - Protects the entire path between two end-points
- The IPsec standard [RFC4301] defined IP security
- Two packet formats are defined:
  - Authentication Header (AH) in [RFC4302]
    - Integrity protection and authentication only
  - Encapsulating Security Payload (ESP) [RFC4303]
    - Also encrypts for confidentiality

- ESP is most widely used
- A mode of ESP defines using AES/CCM [RFC4309]
  - Suitable for use with 6LoWPAN nodes
  - The same L2 IEEE 802.15.4 hardware engine can be applied!

Literature

Literature

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