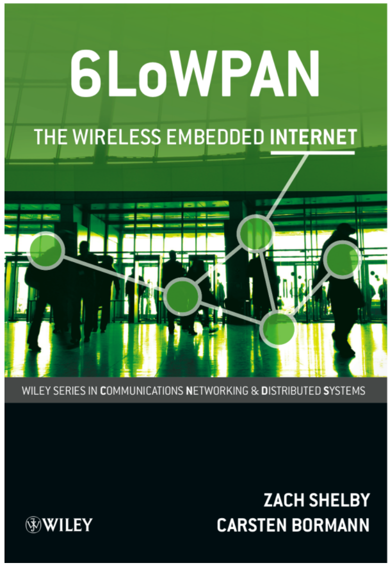
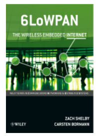
6LoWPAN: The Wireless Embedded Internet

Companion Lecture Slides





The Book

6LoWPAN: The Wireless Embedded Internet

by Zach Shelby, Carsten Bormann

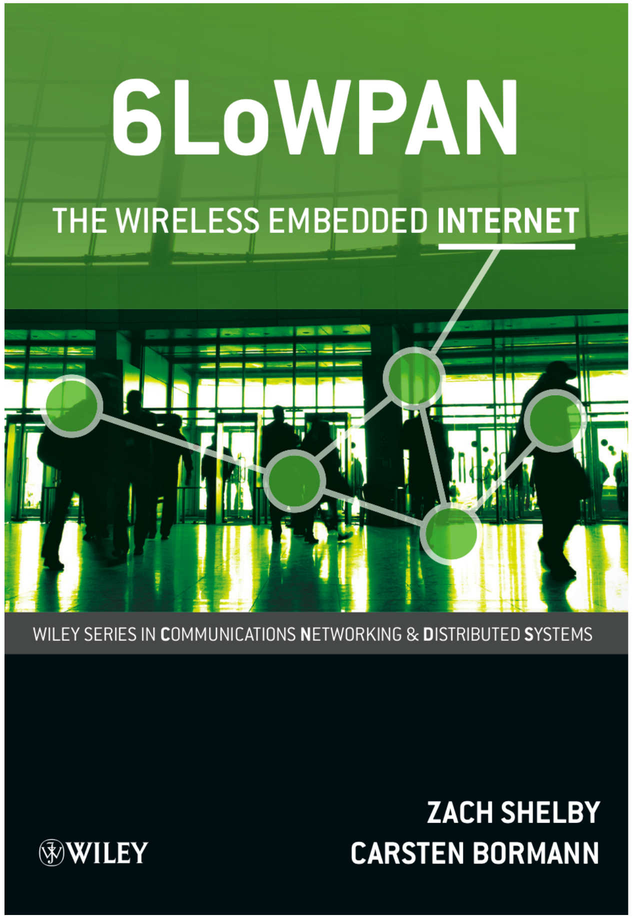
Length: 254 pages

Publisher: John Wiley & Sons

The world's first book on IPv6 over low power wireless networks and the new 6LoWPAN standards.

http://6lowpan.net

Companion web-site with blog, full companion course slides and exercises



How to use these slides

- Designed for use
  - by lecturers in teaching and training
  - by students and researchers
  - as a tutorial to get started
- Recommended course syllabus included
  - Designed as an intensive 2-3 day lecture
  - Laboratory exercise slides for Contiki included
- Creative commons license allows slide re-use
  - For non-commercial purposes with attribution
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- See slide notes for comments and more information
- Useful with the Book's abbreviation, glossary and index

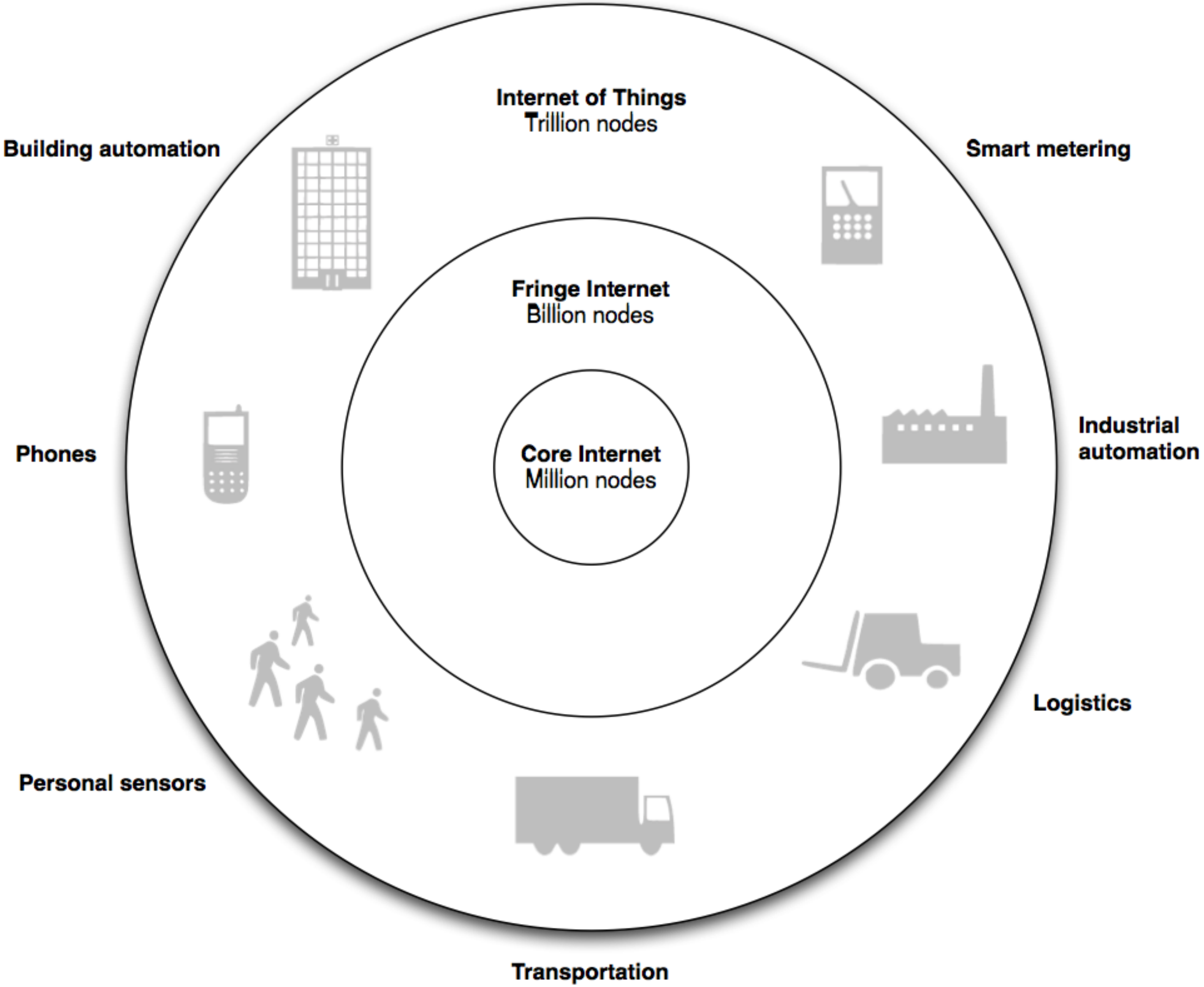
Outline

- Introduction
  - The Internet of Things
  - Applications of 6LoWPAN
- The Internet Architecture and Protocols
- Introduction to 6LoWPAN
- Link-Layer Technologies
  - IEEE 802.15.4
- The 6LoWPAN Format
- Bootstrapping
  - Link-Layer Commissioning
  - Neighbor Discovery

Outline

- Security
- Mobility & Routing
  - IP Mobility Solutions
  - Ad-hoc Routing Protocols
  - The IETF RPL Protocol
- Application Formats and Protocols
- System Examples
  - ISA100 Industrial Automation
  - Wireless RFID Infrastructure
  - Building Energy Savings

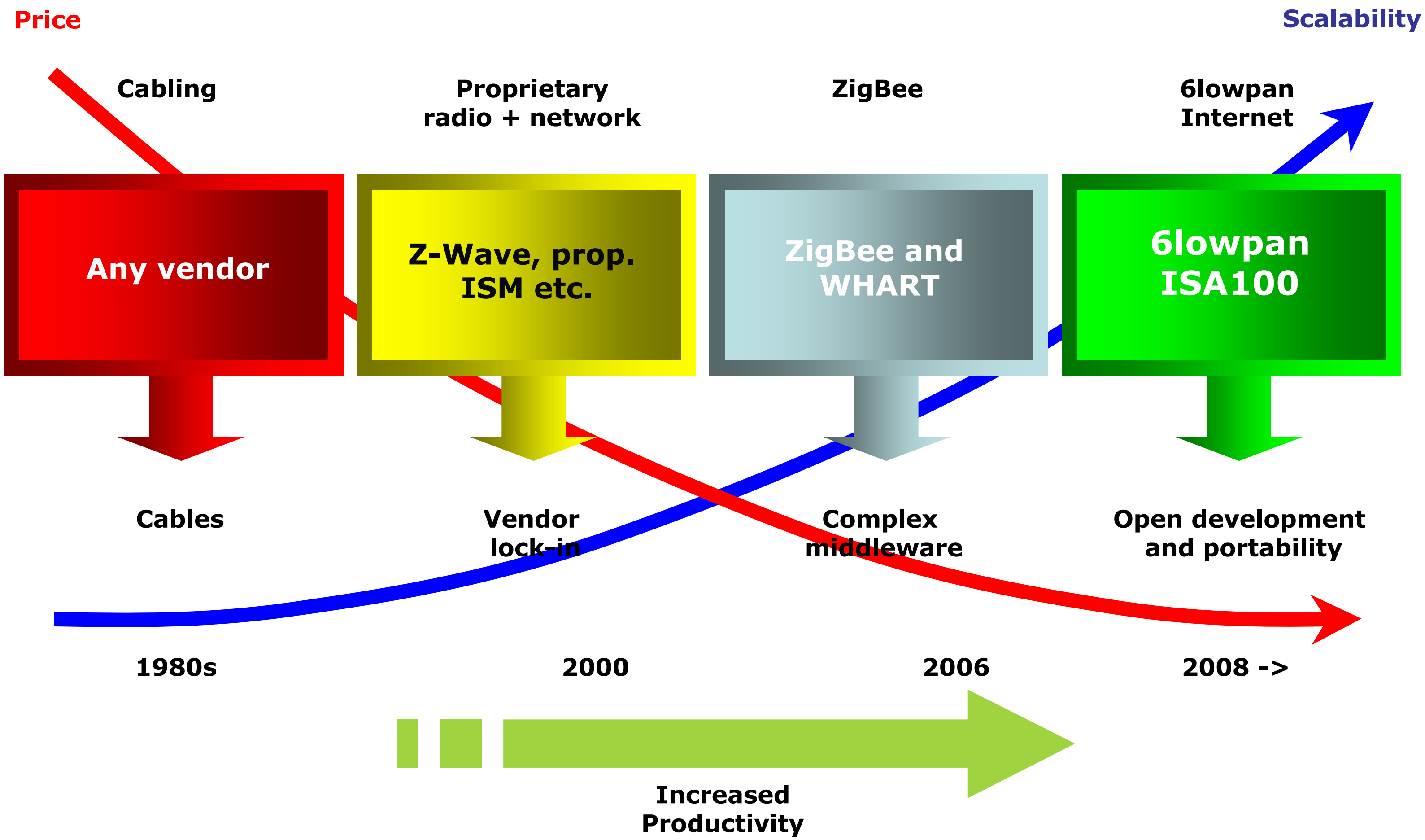
Introduction


Internet of Things
Trillion nodes
Building automation
Smart metering
Fringe Internet
Billion nodes
Core Internet
Million nodes
Phones
Industrial
automation
Logistics
Personal sensors
Transportation

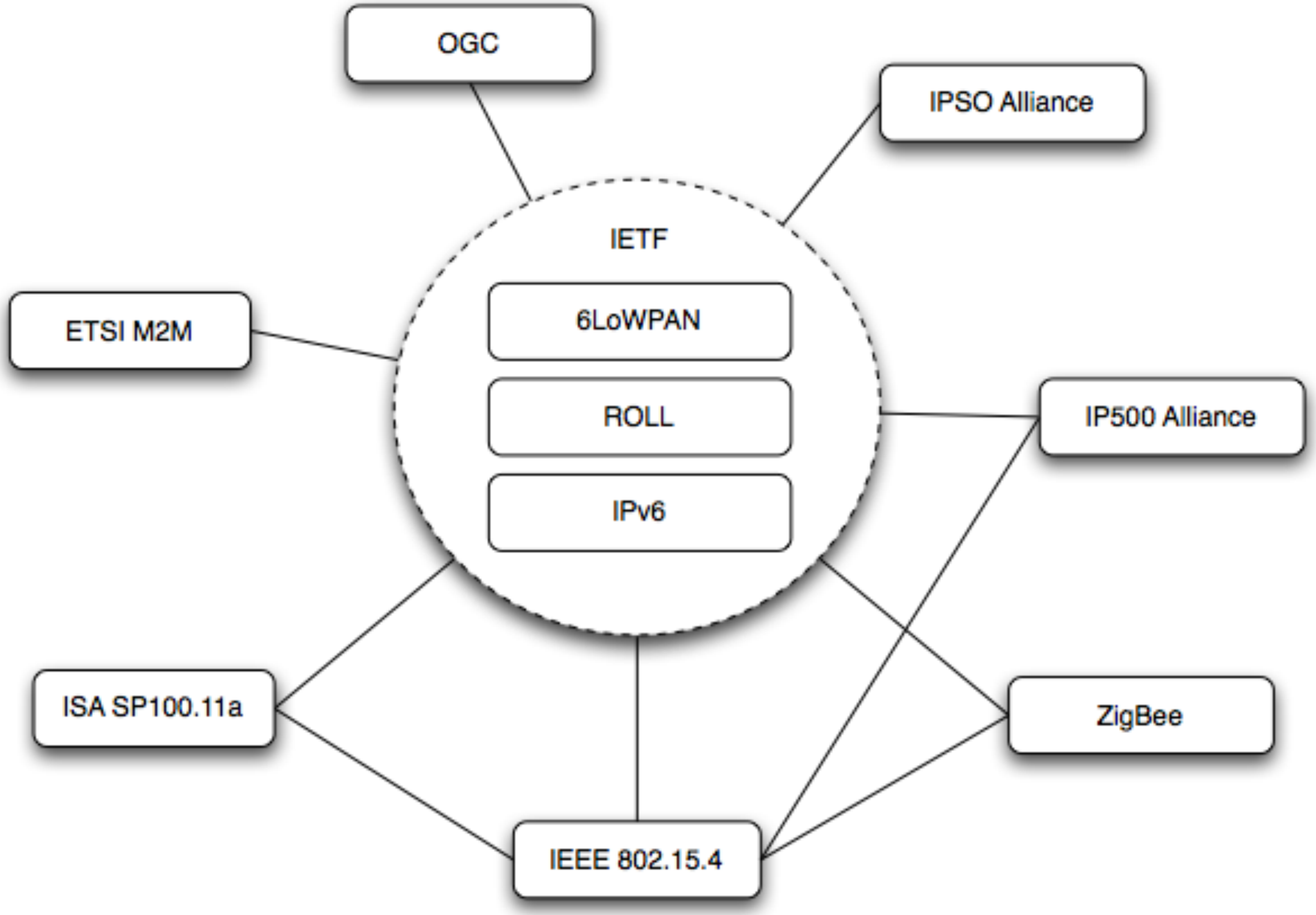
Benefits of 6LoWPAN Technology

- Low-power RF + IPv6 =
  The Wireless Embedded Internet
- 6LoWPAN makes this possible
- The benefits of 6LoWPAN include:
  - Open, long-lived, reliable **standards**
  - **Easy** learning-curve
  - Transparent **Internet** integration
  - Network **maintainability**
  - Global **scalability**
  - **End-to-end** data flows

Evolution of Wireless Sensor Networks



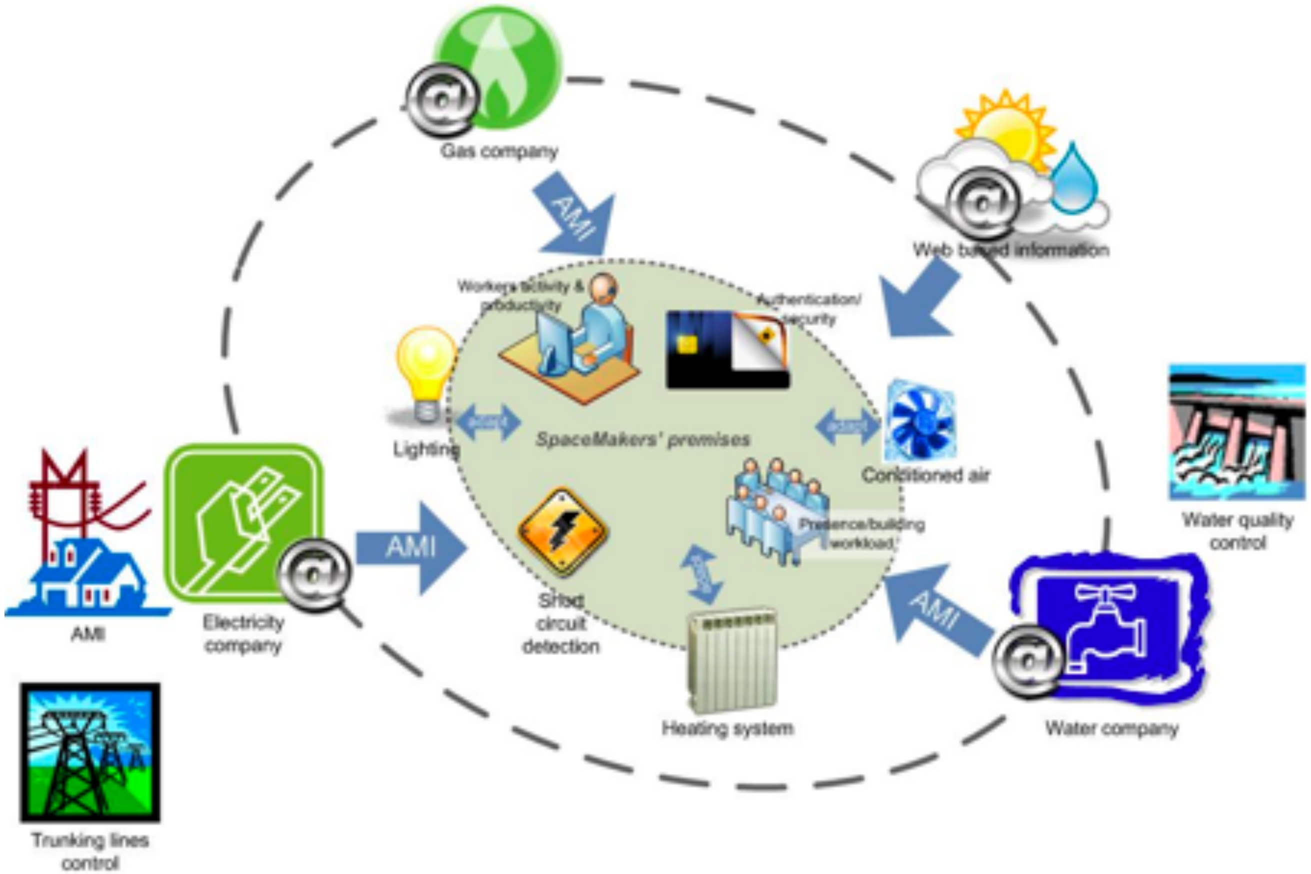
Relationship of Standards



6LoWPAN Applications

- 6LoWPAN has a broad range of applications
  - Facility, Building and Home Automation
  - Personal Sports & Entertainment
  - Healthcare and Wellbeing
  - Asset Management
  - Advanced Metering Infrastructures
  - Environmental Monitoring
  - Security and Safety
  - Industrial Automation
- Examples from the SENSEI project
  - http://www.sensei-project.eu/

Facility Management



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Fitness

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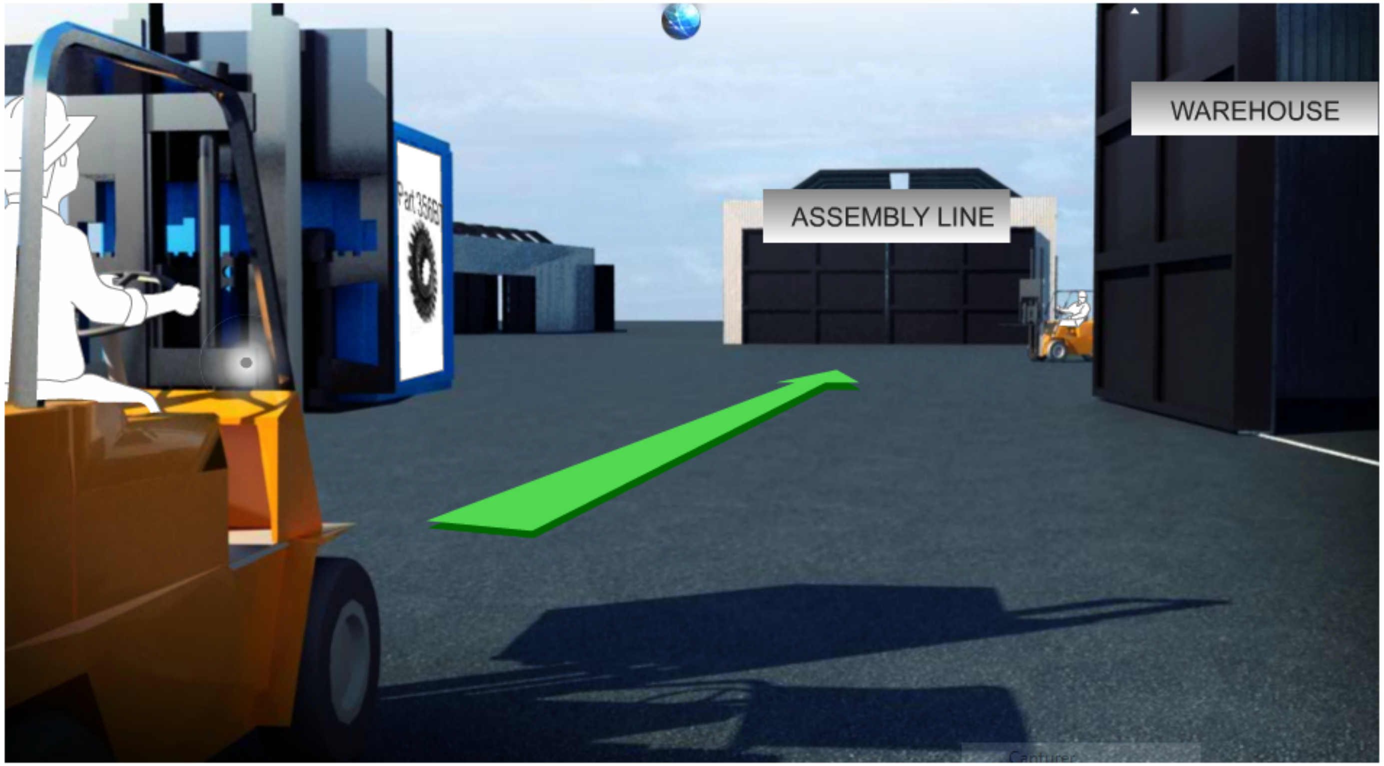
Asset Management



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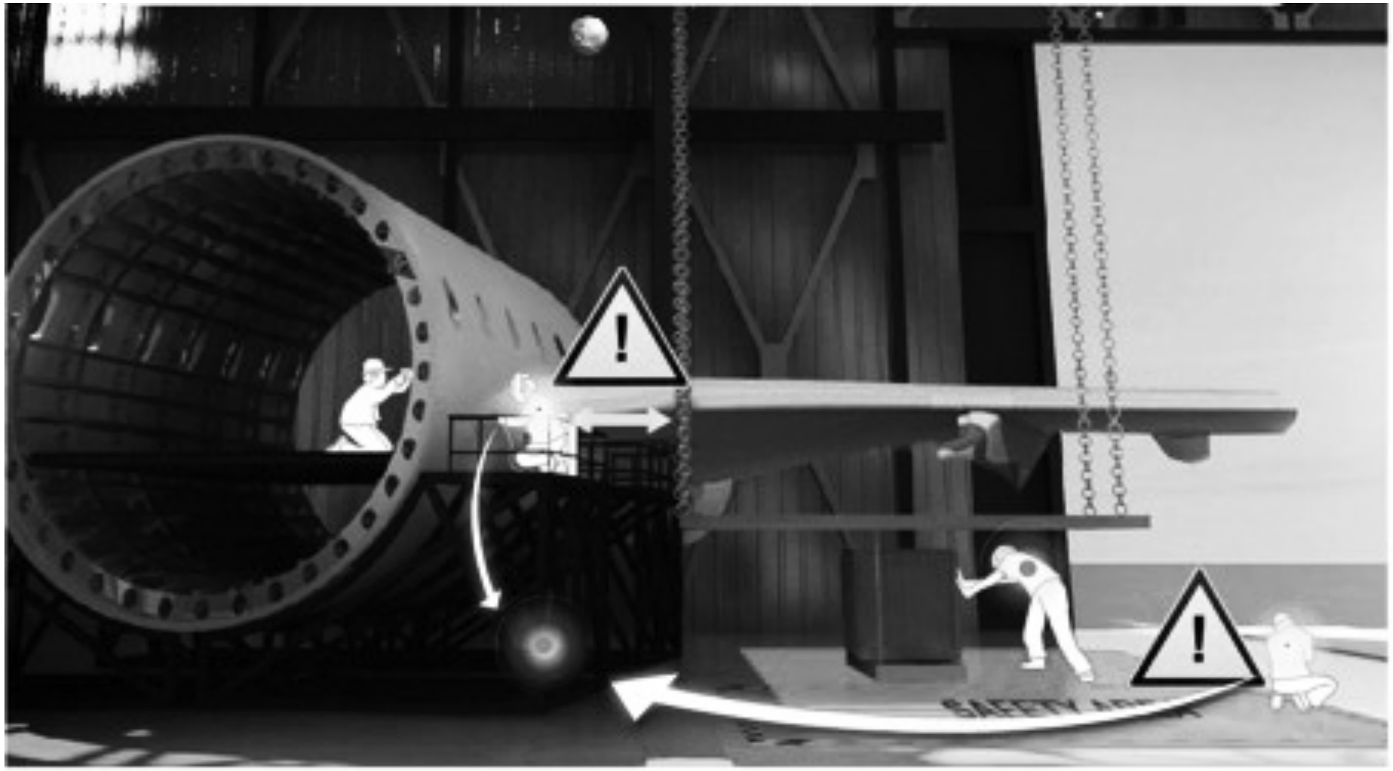
Industrial Automation



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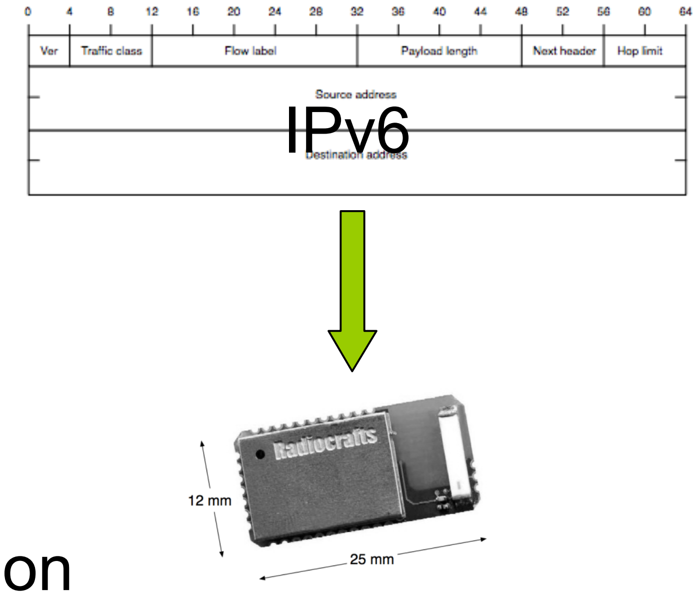
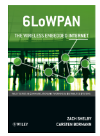
Introduction to 6LoWPAN

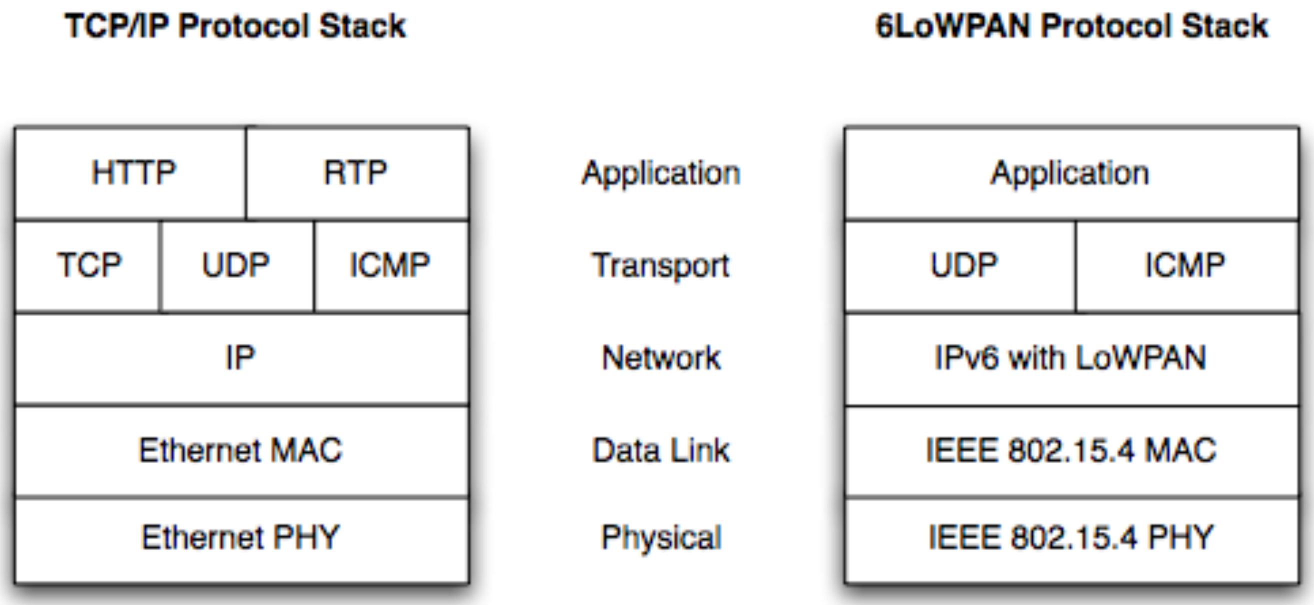
What is 6LoWPAN?

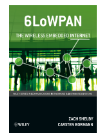
- IPv6 over Low-Power wireless Area Networks
- Defined by IETF standards
  - RFC 4919, 4944
  - draft-ietf-6lowpan-hc and -nd
  - draft-ietf-roll-rpl
- Stateless header compression
- Enables a standard socket API
- Minimal use of code and memory
- Direct end-to-end Internet integration
  - Multiple topology options





Protocol Stack

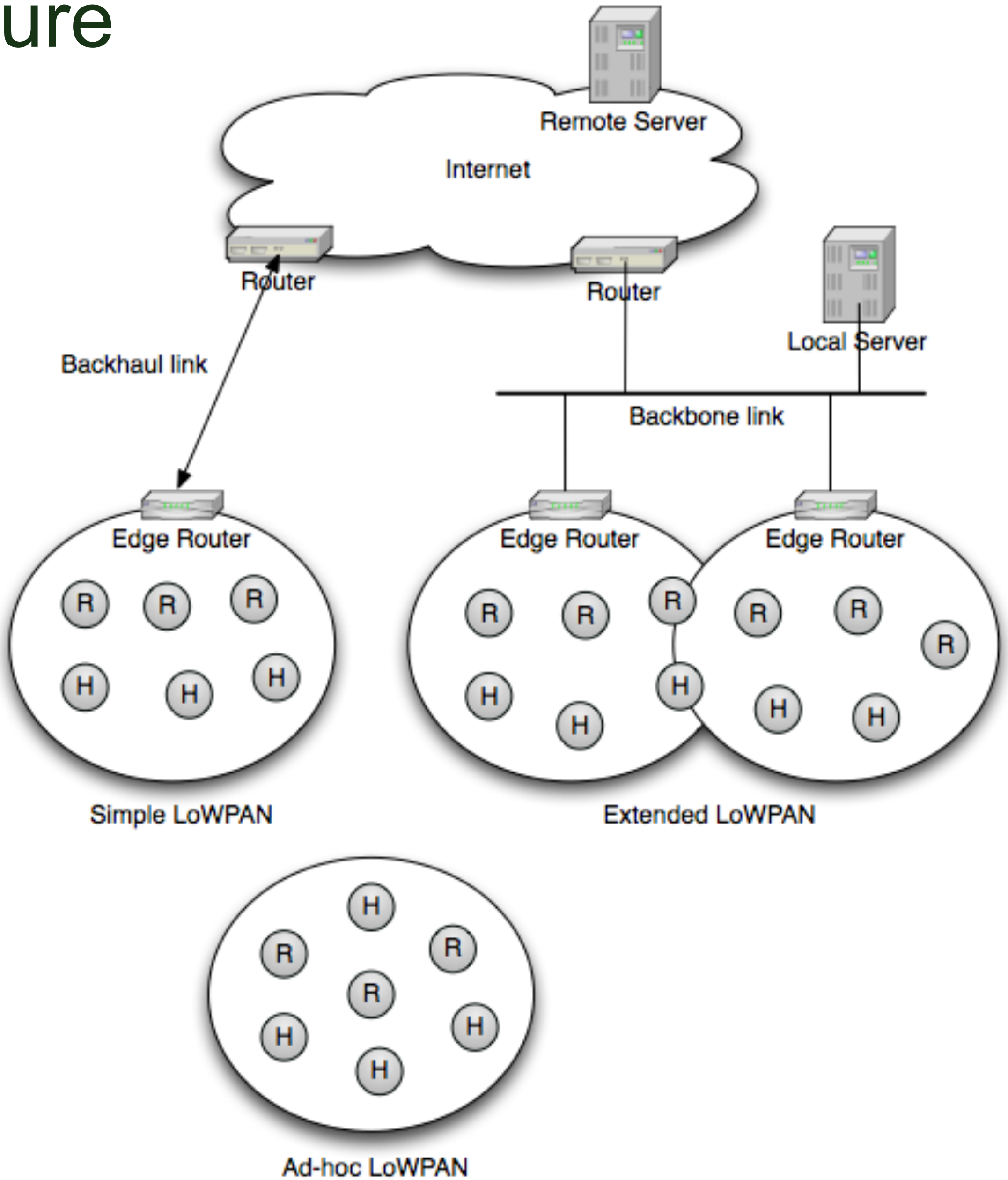




Features

- Support for e.g. 64-bit and 16-bit 802.15.4 addressing
- Useful with low-power link layers such as IEEE 802.15.4, narrowband ISM and power-line communications
- Efficient header compression
  - IPv6 base and extension headers, UDP header
- Network autoconfiguration using neighbor discovery
- Unicast, multicast and broadcast support
  - Multicast is compressed and mapped to broadcast
- Fragmentation
  - 1280 byte IPv6 MTU -> 127 byte 802.15.4 frames
- Support for IP routing (e.g. IETF RPL)
- Support for use of link-layer mesh (e.g. 802.15.5)

Architecture

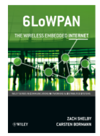


Architecture

- LoWPANs are stub networks
- Simple LoWPAN
  - Single Edge Router
- Extended LoWPAN
  - Multiple Edge Routers with common backbone link
- Ad-hoc LoWPAN
  - No route outside the LoWPAN
- Internet Integration issues
  - Maximum transmission unit
  - Application protocols
  - IPv4 interconnectivity
  - Firewalls and NATs
  - Security

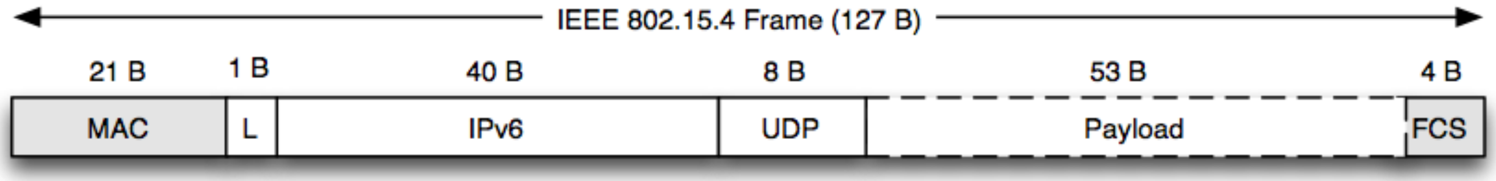
<table>
<tr><td colspan="2">IPv6</td></tr>
<tr><td rowspan="2">Ethernet MAC</td><td>LoWPAN Adaptation</td></tr>
<tr><td>IEEE 802.15.4 MAC</td></tr>
<tr><td>Ethernet PHY</td><td>IEEE 802.15.4 PHY</td></tr>
</table>

IPv6-LoWPAN Router Stack

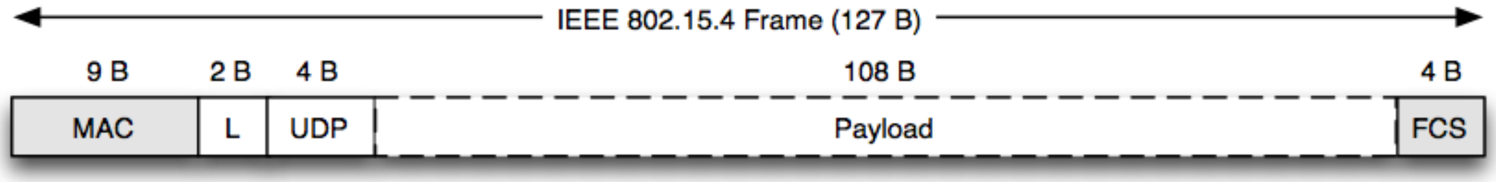


6LoWPAN Headers

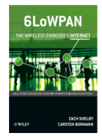
- Orthogonal header format for efficiency
- Stateless header compression



Full UDP/IPv6 (64-bit addressing)



Minimal UDP/6LoWPAN (16-bit addressing)

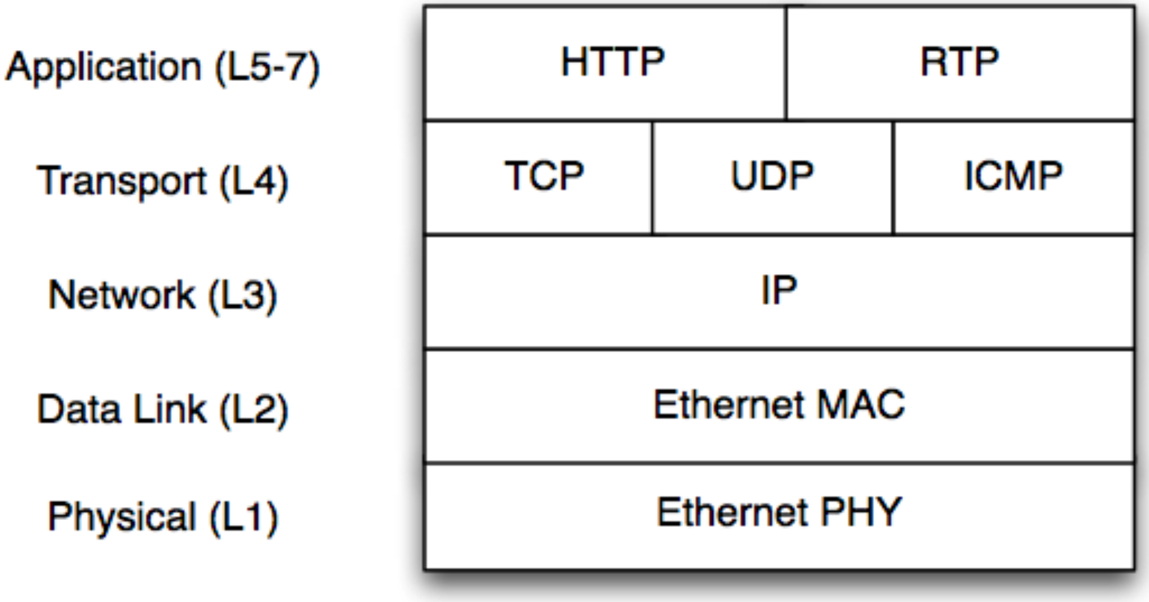


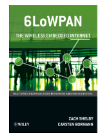
The Internet Architecture & Protocols

The Internet

- A global, publicly accessible, series of interconnected computer networks (made up of hosts and clients) using the packet-switched Internet Protocol
- Consists of millions of small network domains
- ICANN, the Internet Corporation for Assigned Names and Numbers
  - Unique identifiers, domain names, IP addresses, protocol ports etc.
  - Only a coordinator, not a governing body
- These days an Internet Governance Forum (IGF) has been formed to discuss global governance
- Internet-related protocols are standardized by the Internet Engineering Task Force (IETF)

IP Protocol Stack





Internet Architecture

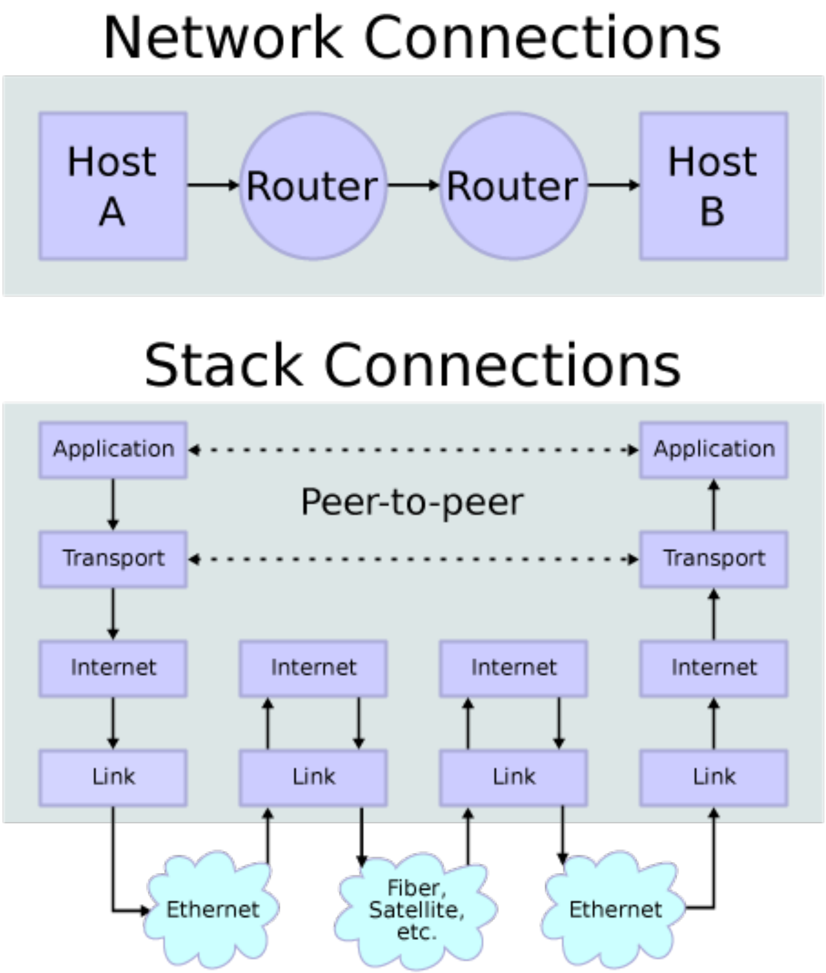


Image source: (Wikipeida) GFDL

Internet Protocol v6

- IPv6 (RFC 2460) = the next generation Internet Protocol
  - Complete redesign of IP addressing
  - Hierarchical 128-bit address with decoupled host identifier
  - Stateless auto-configuration
  - 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

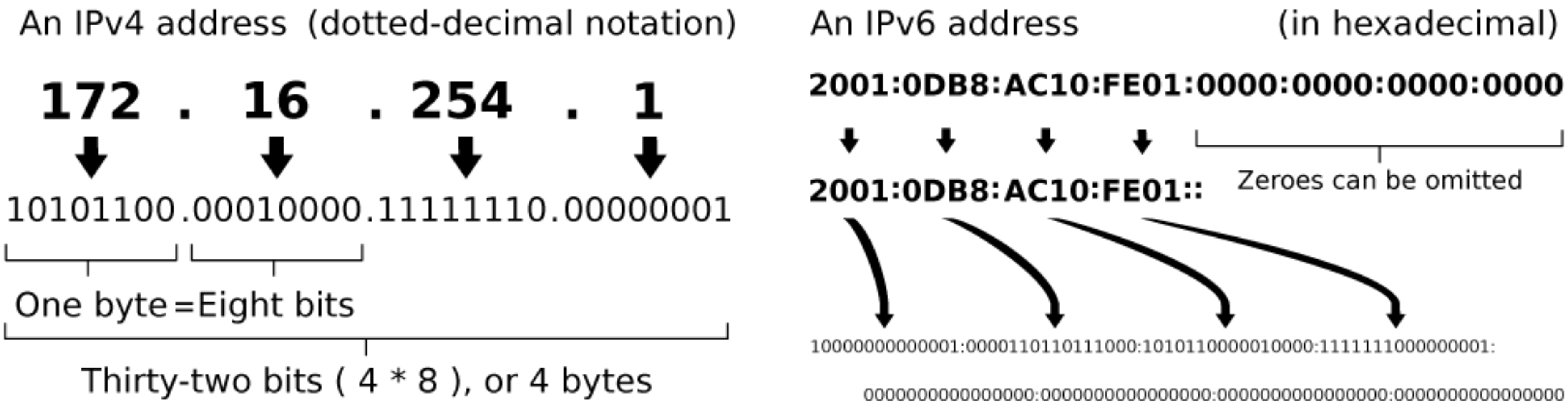
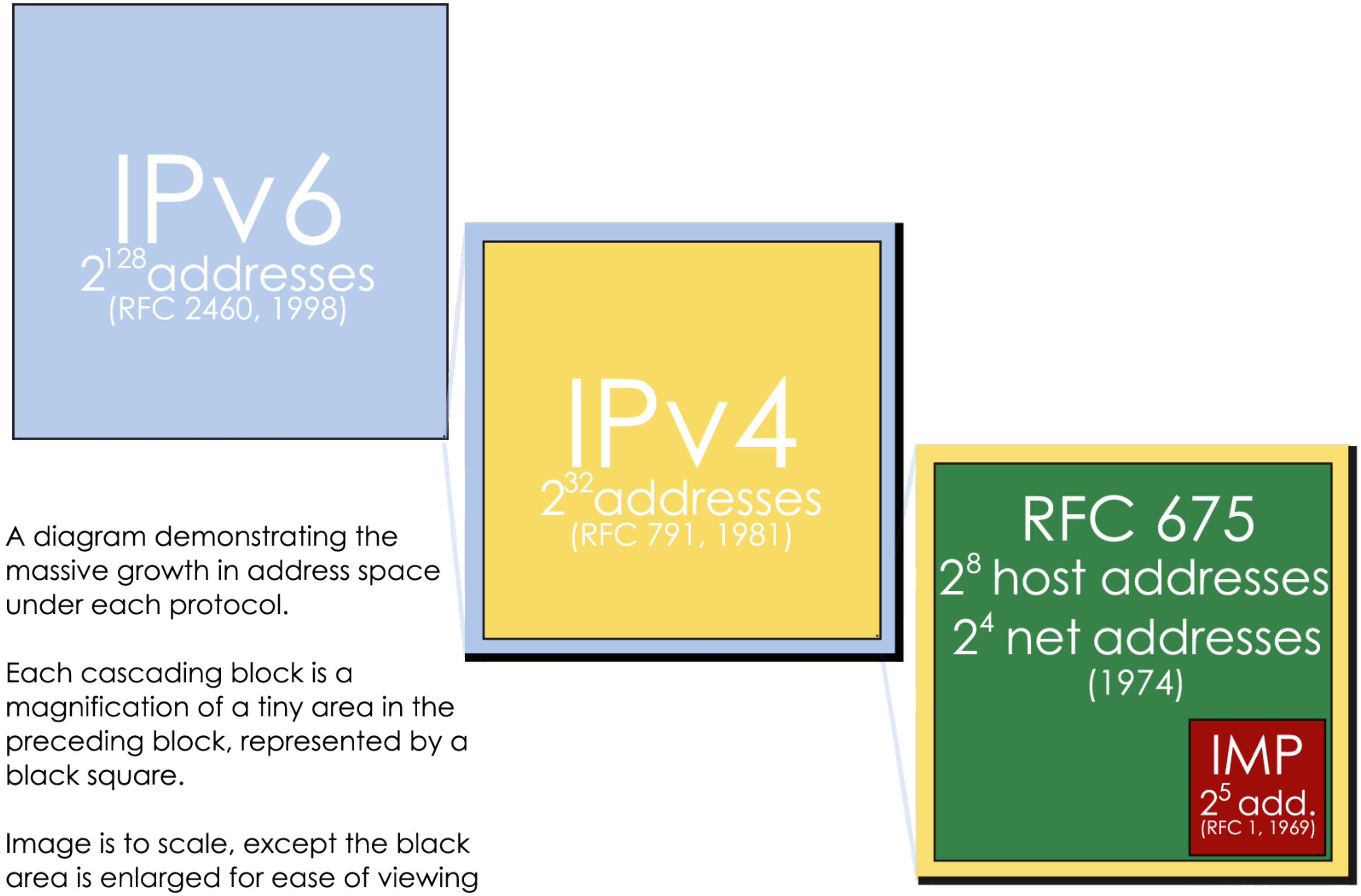


Image source: Indeterminant (Wikipeida) GFDL

Address Space Comparison



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IPv4 vs. IPv6 Header

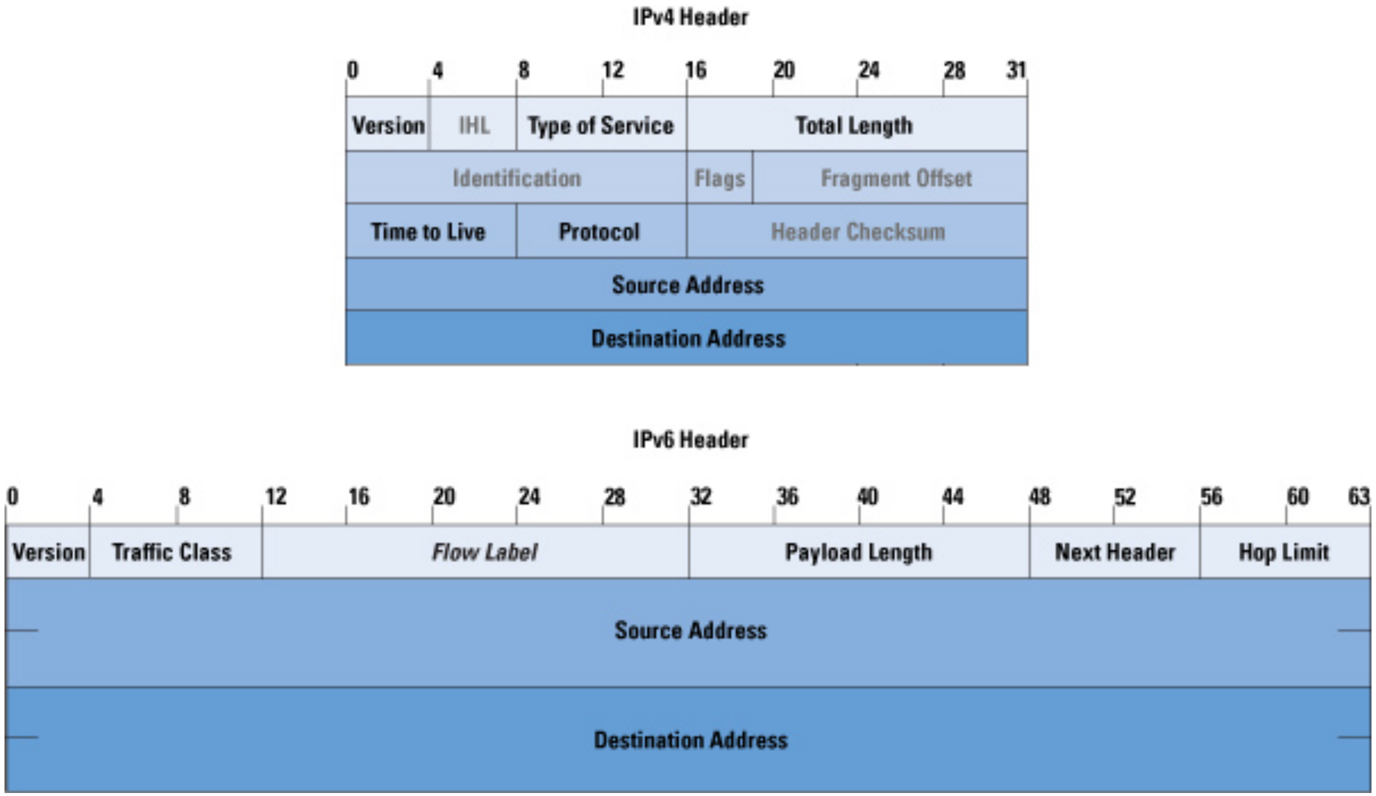
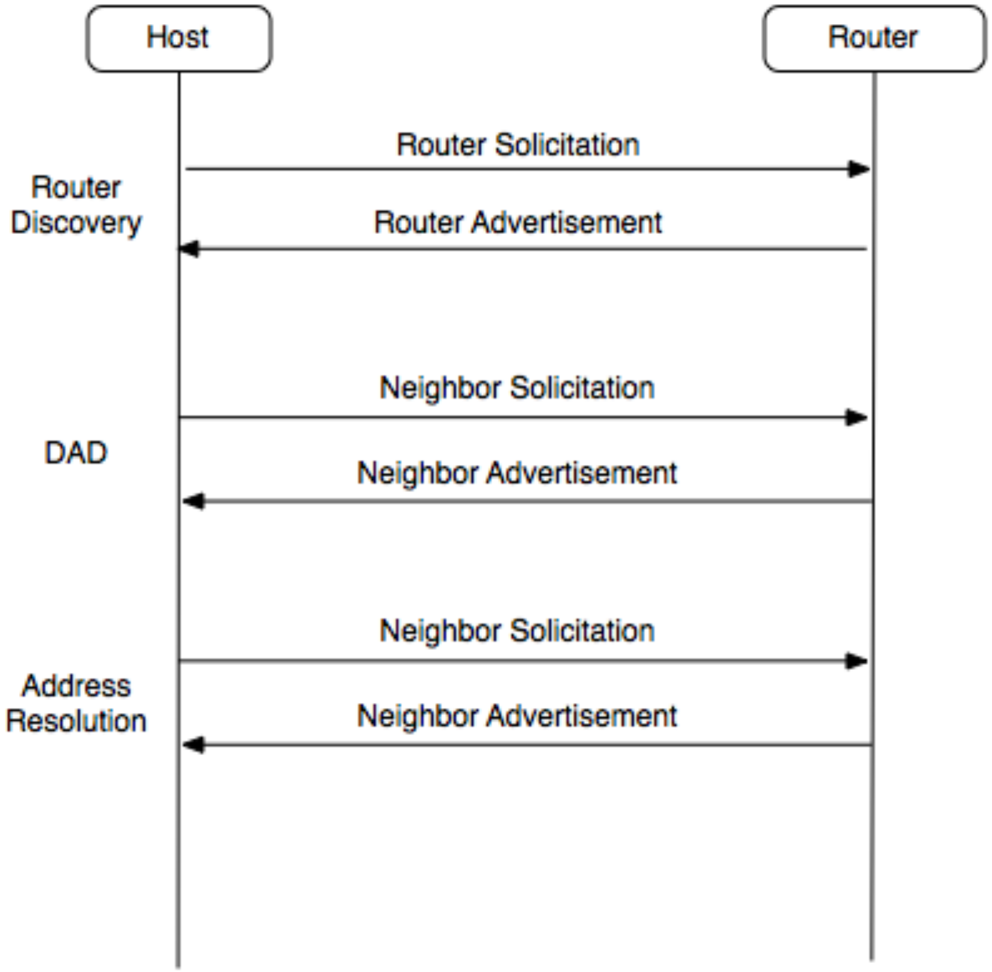


Image source: Bino1000, Mkim (Wikipeida) GFDL

IPv6 Neighbor Discovery

- IPv6 is the format - ND is the brains
  - "One-hop routing protocol" defined in RFC4861
- Defines the interface between neighbors
- Finding Neighbors
  - Neighbor Solicitation / Neighbor Acknowledgement
- Finding Routers
  - Router Solicitation / Router Advertisement
- 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

- The Internet Control Message Protocol (ICMPv6)
  - Defined by RFC2463
  - 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

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

- The Transmission Control Protocol (TCP) (RFC 793)
  - 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

```
 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

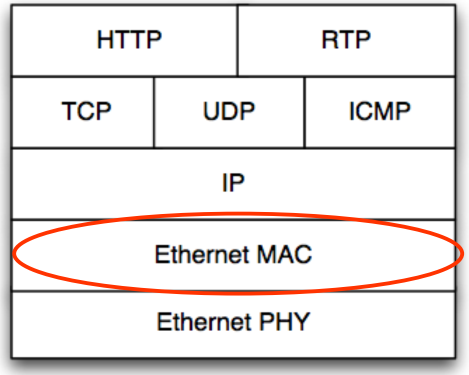
- The User Datagram Protocol (UDP) (RFC 768)
  - Used to deliver short messages over IP
  - Unreliable, connectionless protocol
  - Can be used with broadcast and multicast
  - Common in streaming and VoIP, DNS and network tools

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

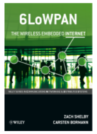
Link Layer Technologies

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

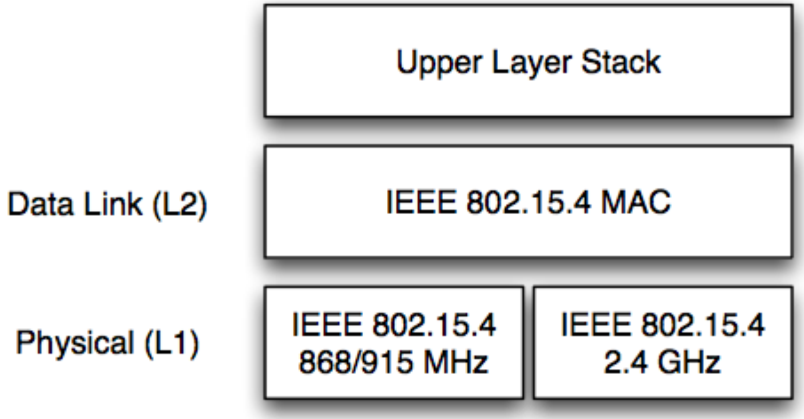


Medium Access Control

- The sharing of a radio by multiple independent devices
- There are multiple ways to share a radio
  - Frequency Division Multiple Access
  - Time Division Multiple Access
  - Carrier Sense Multiple Access
  - Code Division Multiple Access
  - Hybrids of the above
- MAC algorithms also take care of
  - Acknowledgements for packets
  - Link topology and addressing
  - Error checking and link security

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

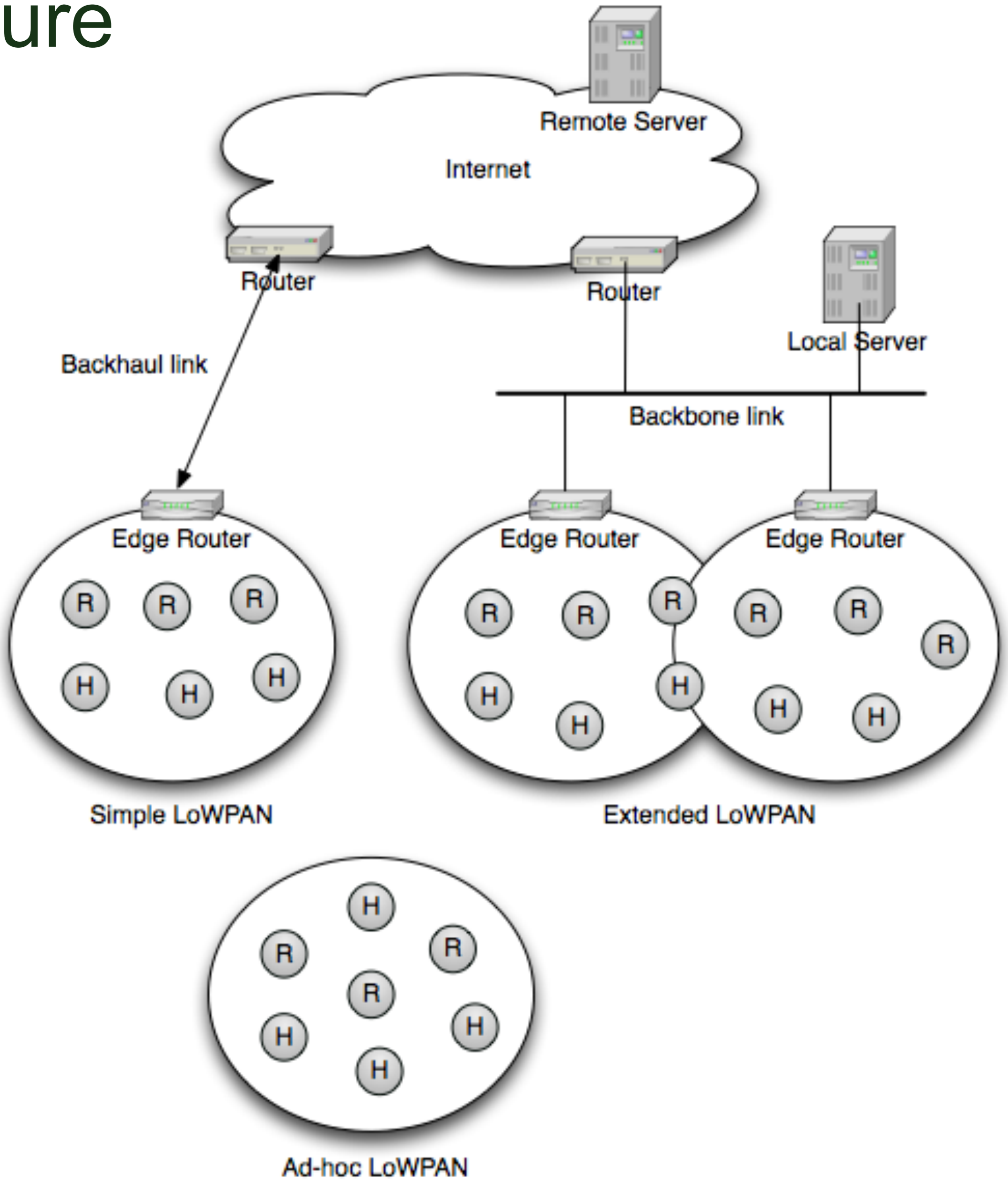


Other Link-Layers for 6LoWPAN

- 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

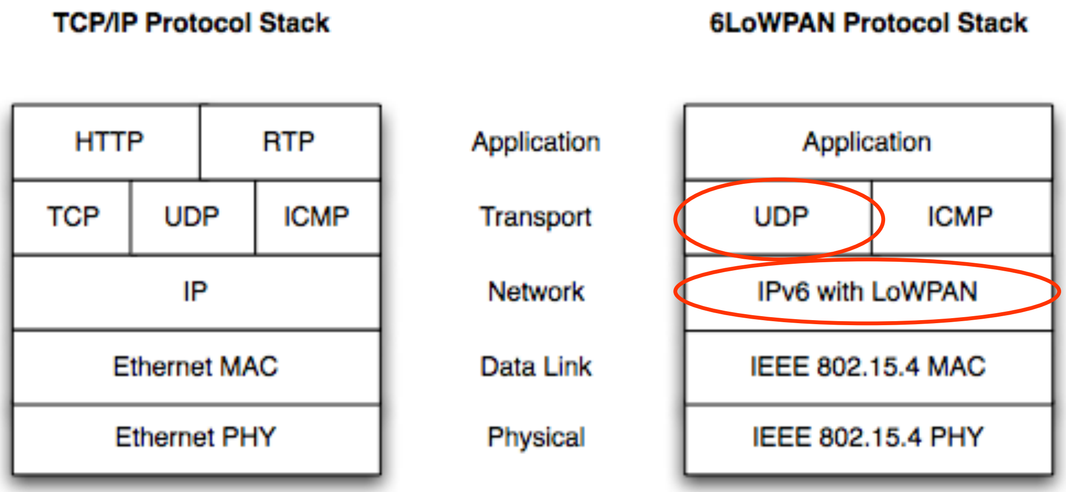
The 6LoWPAN Format

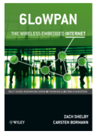
Architecture



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 draft-ietf-6lowpan-hc (work in progress)





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
- draft-ietf-6lowpan-hc Features:
  - New HC (IPv6 header) and NHC (Next-header) compression
  - Support for global address compression (with contexts)
  - Support for IPv6 option header compression
  - Support for compact multicast address compression

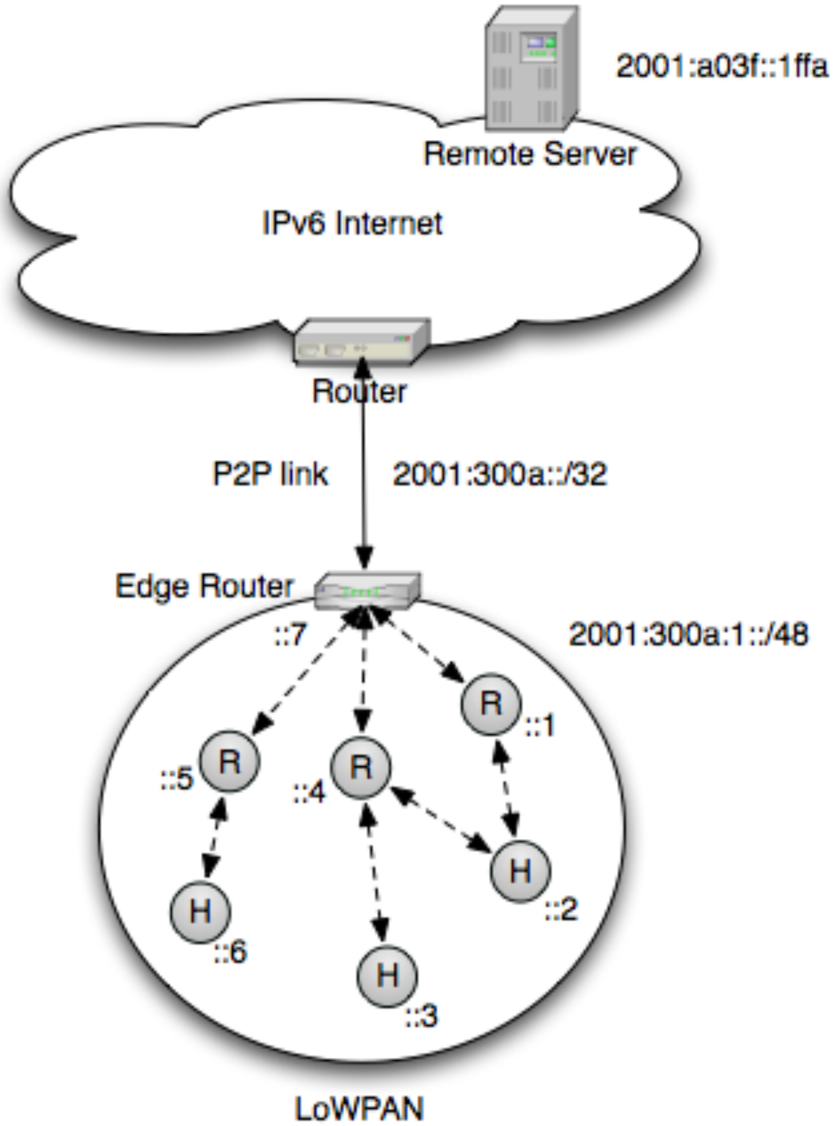
IPv6 Addressing

- 128-bit IPv6 address = 64-bit prefix + 64-bit Interface ID (IID)
- 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 (RFC2462)
- 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

Addressing Example

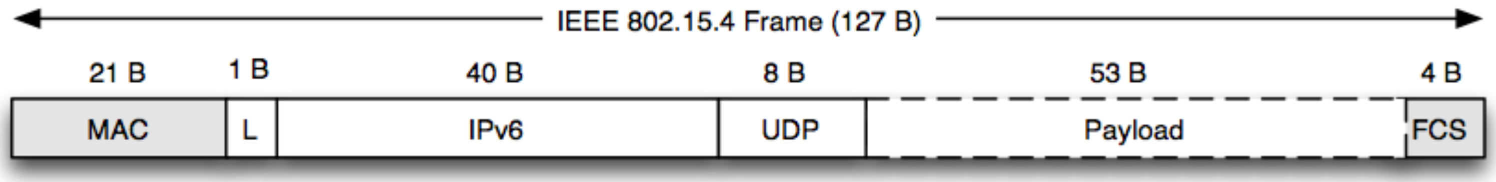


UDP/IPv6 Headers

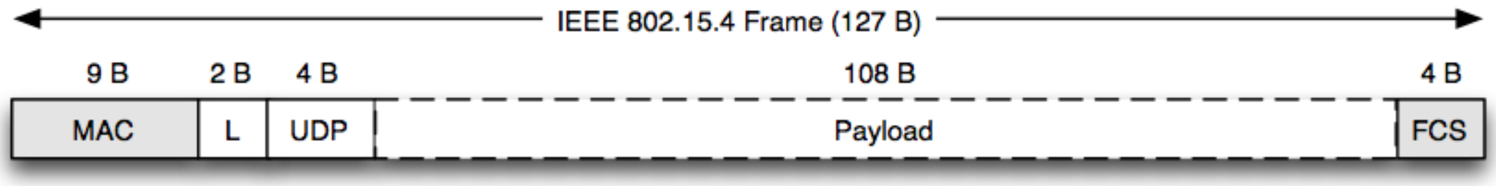
48 Bytes!

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

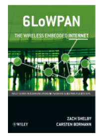
Header Comparison



Full UDP/IPv6 (64-bit addressing)



Minimal UDP/6LoWPAN (16-bit addressing)



LoWPAN UDP/IPv6 Headers

6 Bytes!

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        ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Payload

draft-ietf-6lowpan-hc

IP Header Compression (IPHC)

Base Header

```
 +-------------------------------------+-----------------------
 | Dispatch + LOWPAN_IPHC (2-3 octets) | Compressed IPv6 Header
 +-------------------------------------+-----------------------
```

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

draft-ietf-6lowpan-hc

Next-header Compression (NHC)

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

draft-ietf-6lowpan-hc

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
- Fragment recovery is currently under IETF consideration

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          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+

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

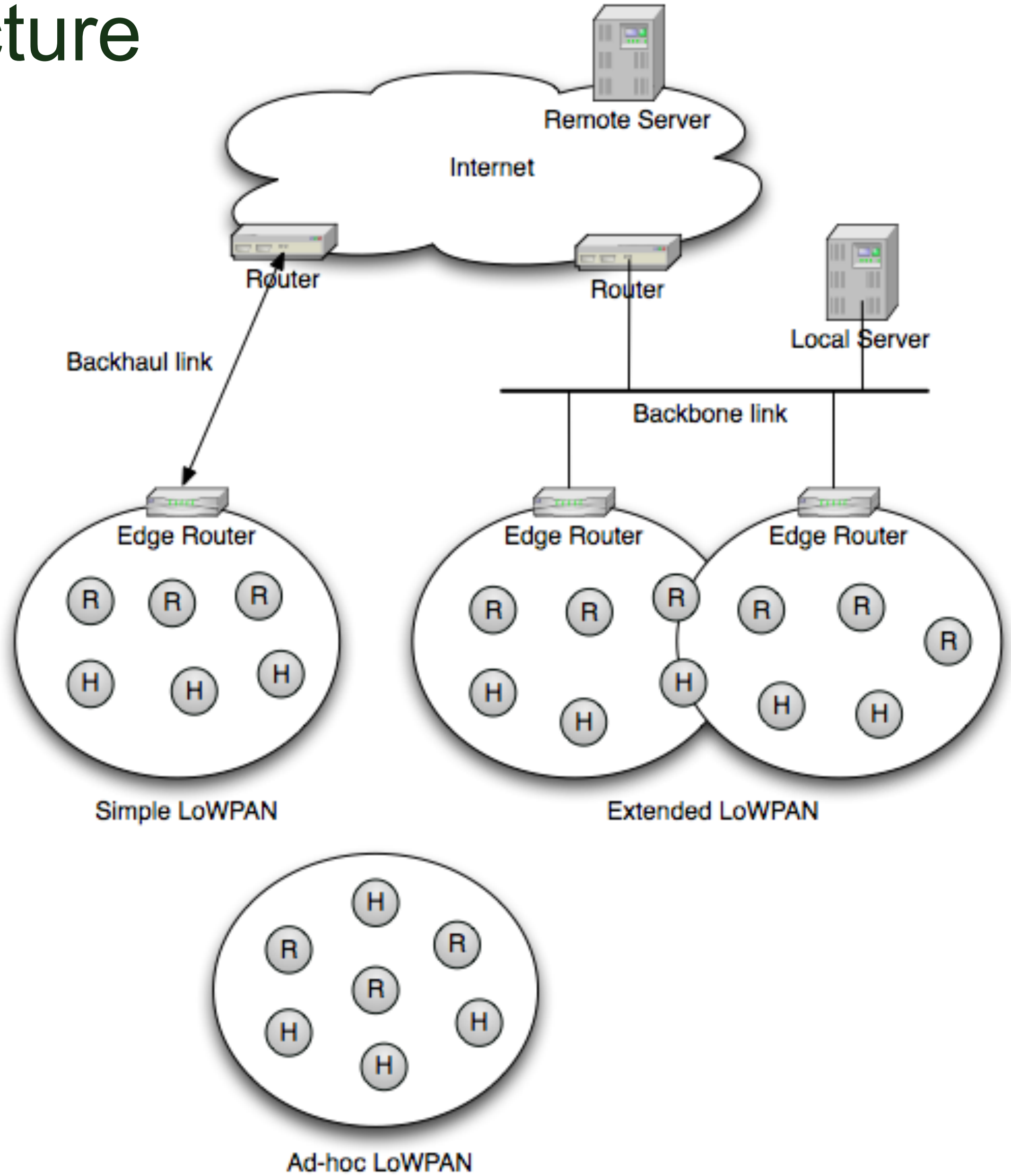
Link-layer Commissioning

- 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

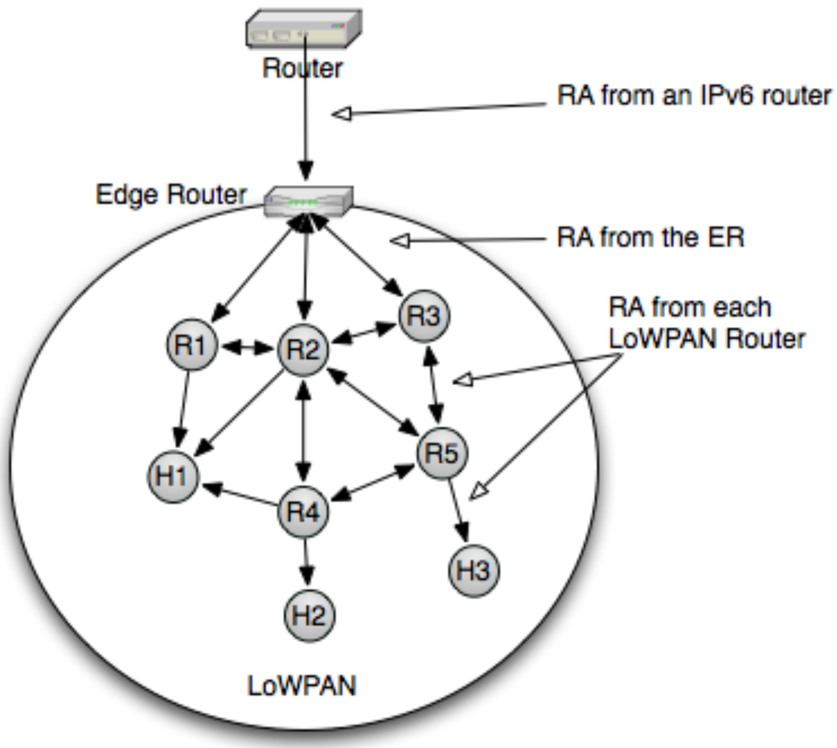
- Standard ND for IPv6 is not appropriate for 6LoWPAN:
  - Assumption of a single link for an IPv6 subnet prefix
  - Assumption that nodes are always on
  - Heavy use of multicast traffic (broadcast/flood in 6LoWPAN)
  - No efficient multihop support over e.g. 802.15.4
- 6LoWPAN Neighbor Discovery provides:
  - 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 draft-ietf-6lowpan-nd (work in progress)

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



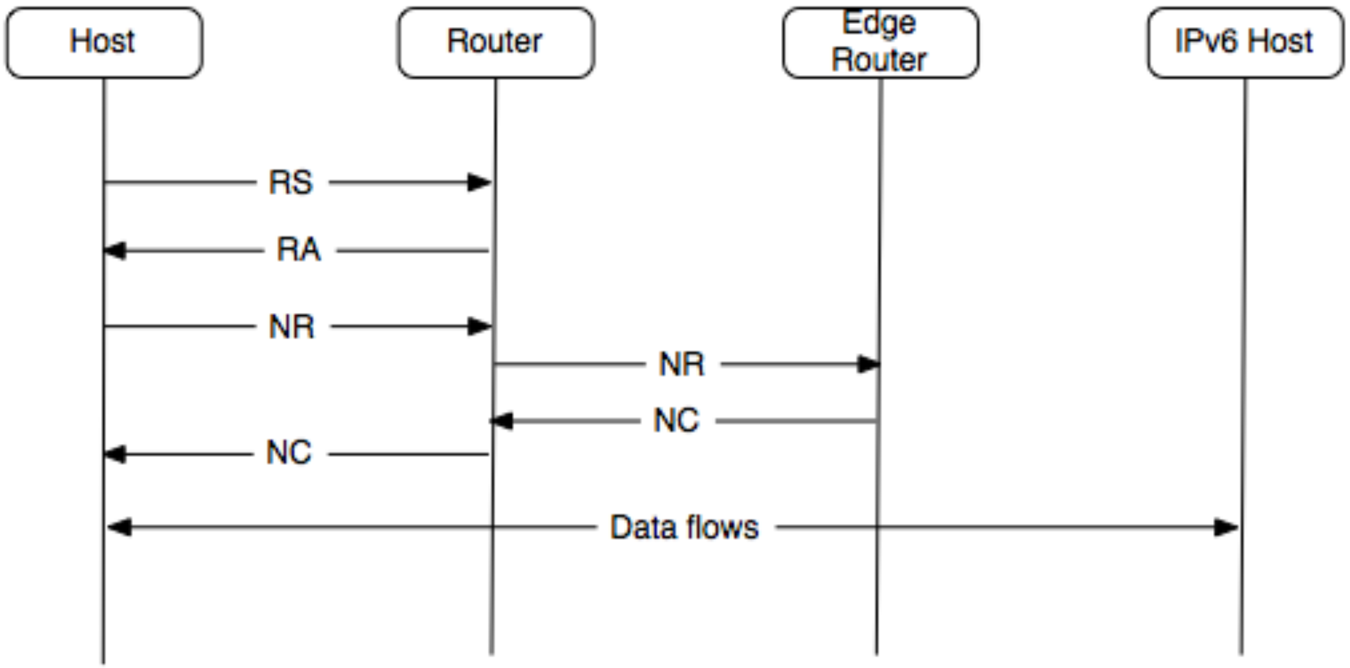
Node Registration

- 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

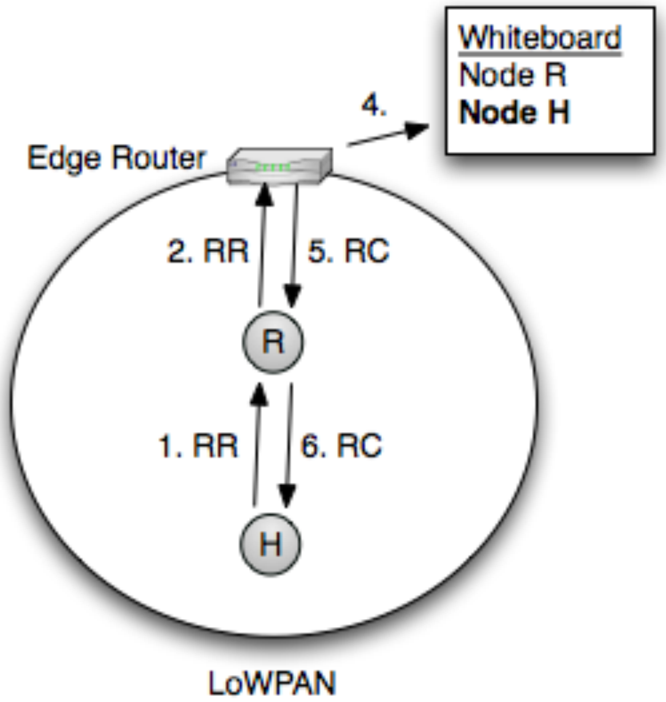
```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| Type (NR)/(NC)|     Code      |          Checksum             |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+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

Typical 6LoWPAN-ND Exchange



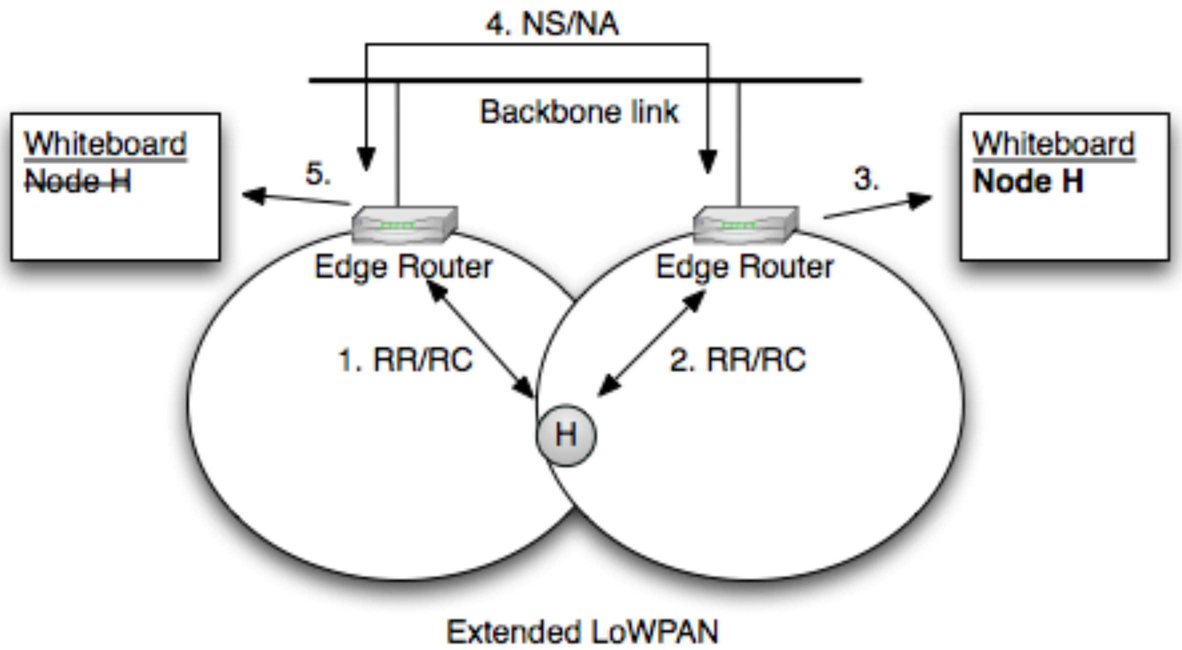
The Whiteboard

- 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

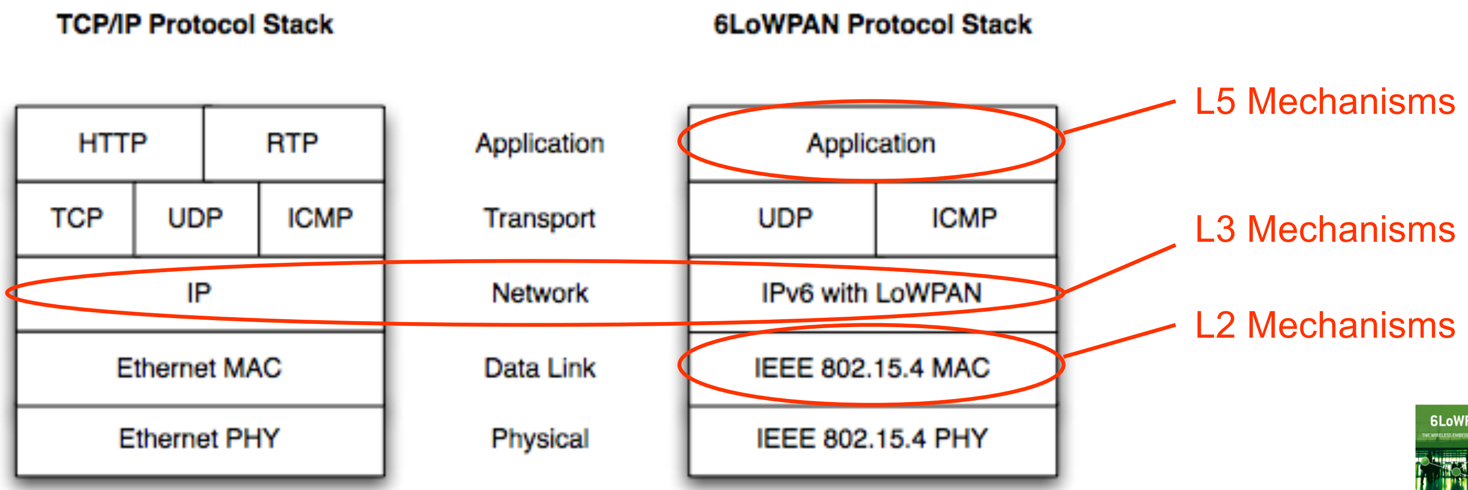
- Extended LoWPANs consist of two or more LoWPANs:
  - Which share the same IPv6 prefix
  - Which are connected together by a backbone link
- Whiteboards are synchronized over the backbone link



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!

ESP 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
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+ ----
|               Security Parameters Index (SPI)                 | I
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+ I
|                      Sequence Number                          | I
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+ I --
|                    Payload Data* (variable)                   | I C
:                                                               : I C
|                                                               | I C
+               +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+ I C
|               |     Padding (0-255 bytes)                     | I C
+-+-+-+-+-+-+-+-+               +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+ I C
|                               |  Pad Length   | Next Header   | I C
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+ ----
|         Integrity Check Value-ICV   (variable)                |
:                                                               :
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Mobility & Routing

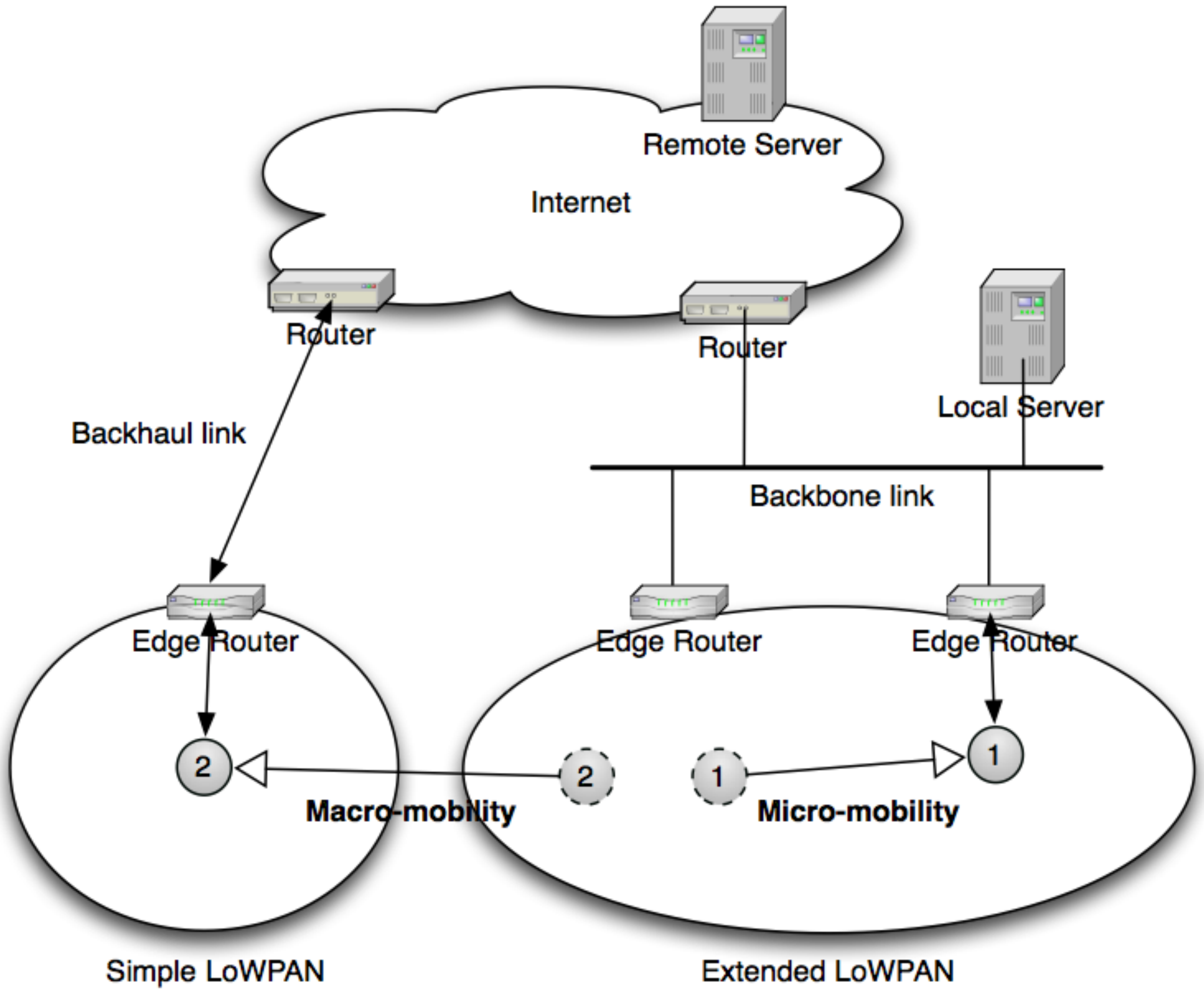
What is Mobility?

© SENSEI Consortium

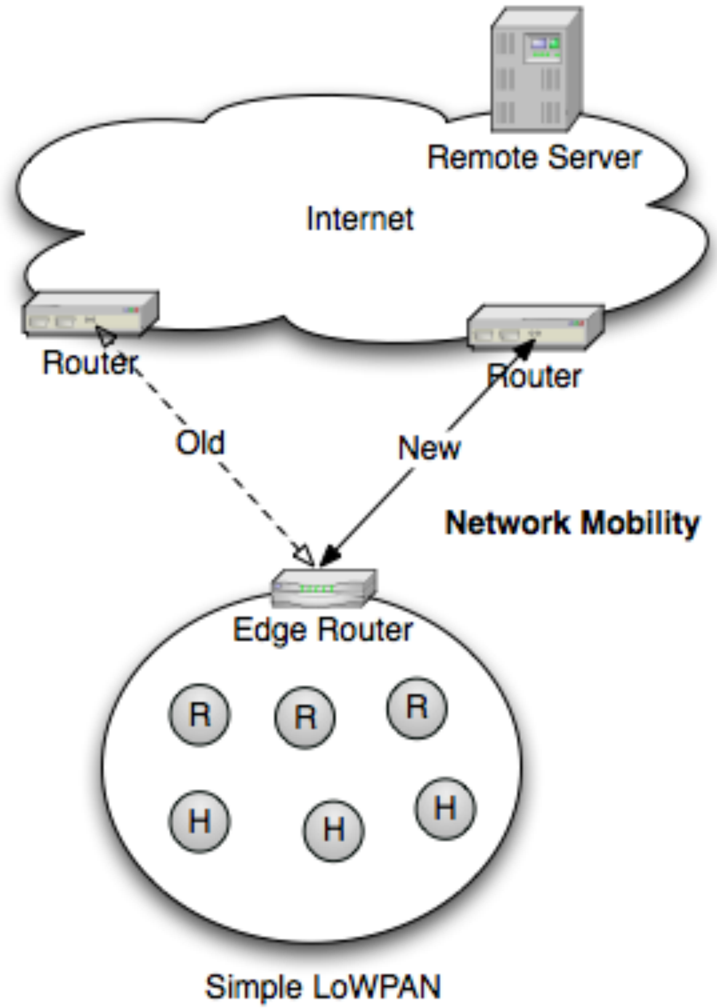
Types of Mobility

- Mobility involves two processes
  - Roaming - *moving from one network to another*
  - Handover - *changing point of attachment (and data flows)*
- Mobility can be categorized as
  - Micro-mobility - *within a network domain*
  - Macro-mobility - *between network domains (IP address change)*
- Consider also *Node* vs. *Network* mobility
- What causes mobility?
  - Physical movement
  - Radio channel
  - Network performance
  - Sleep schedules
  - Node failure

Node Mobility



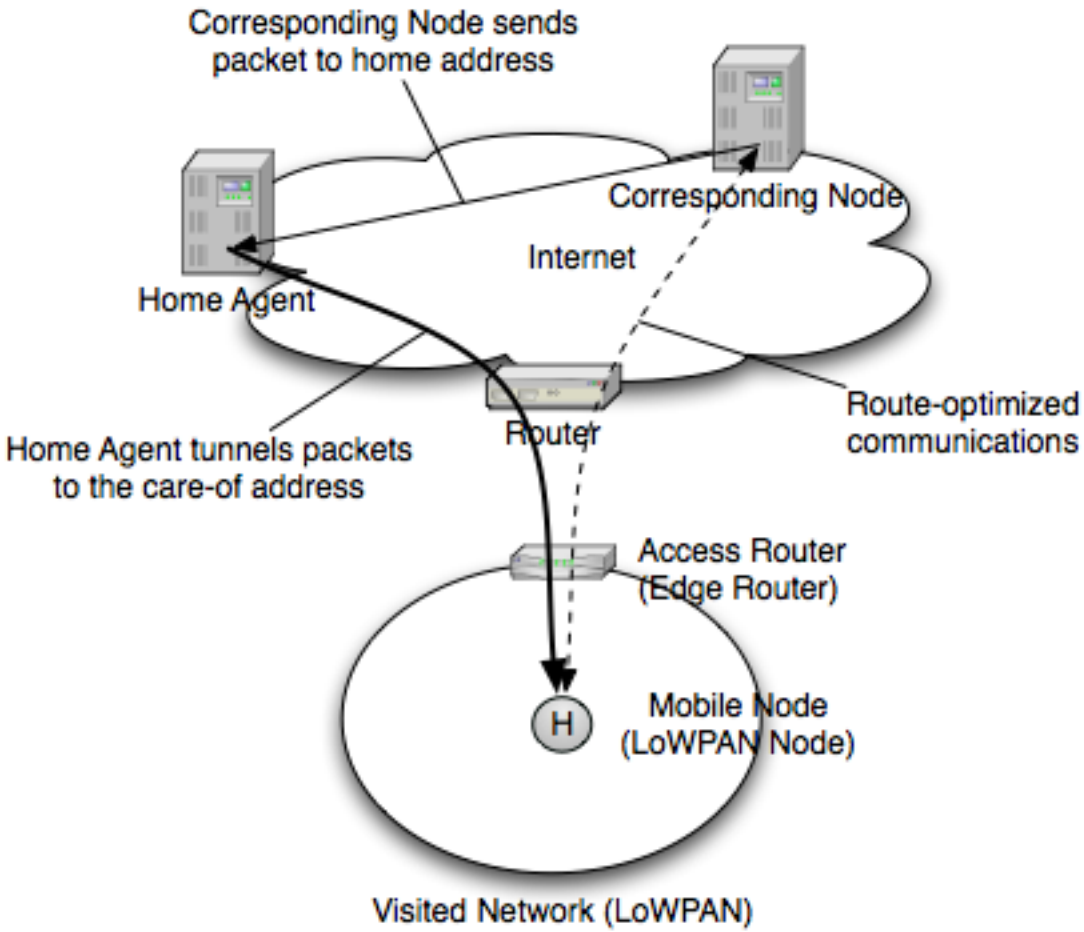
Network Mobility



Dealing with Mobility

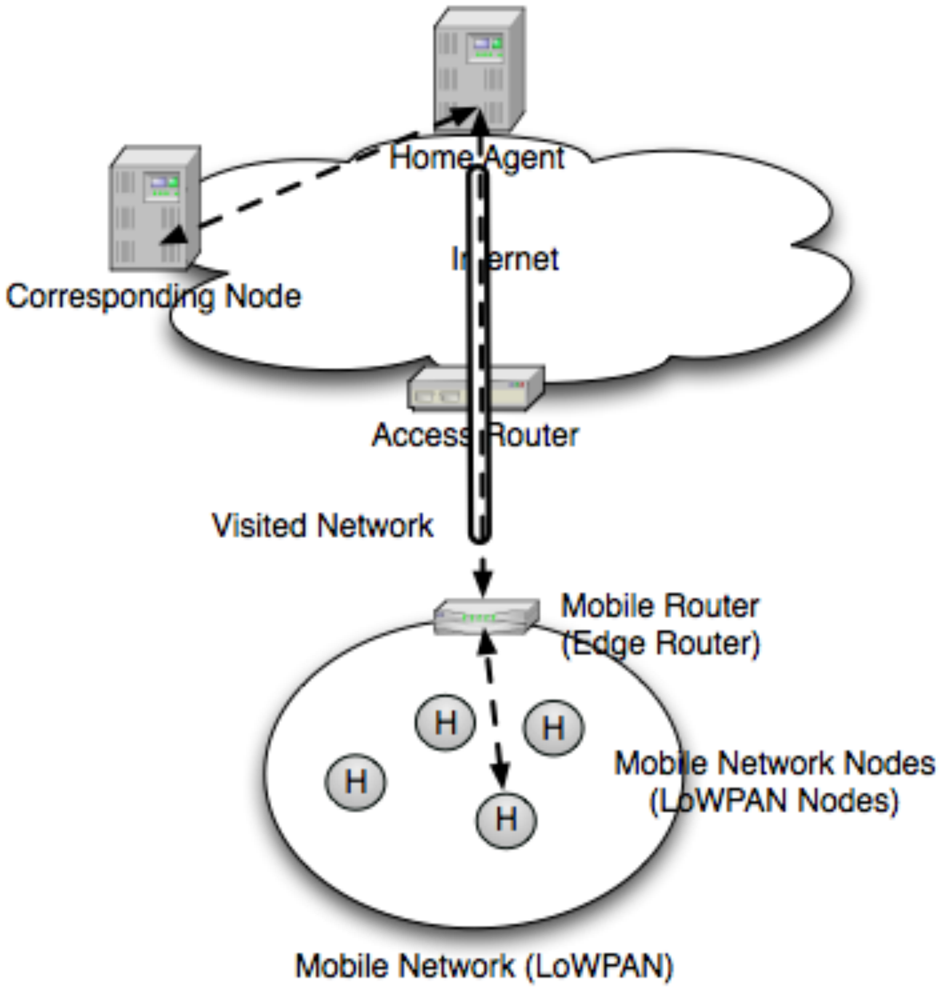
- Micro-mobility
  - Do nothing (restart)
  - Link-layer techniques (e.g. GPRS, WiFi)
  - 6LoWPAN-ND extended LoWPANs
  - Routing also plays a role
- Macro-mobility
  - Do nothing (restart)
  - Application layer (SIP, UUID, DNS)
  - Mobile IPv6 [RFC3775]
  - Proxy Home Agent
- Network mobility
  - Do nothing (restart all nodes)
  - NEMO [RFC3963]

MIPv6



Corresponding Node sends
packet to home address
Corresponding Node
Internet
Home Agent
Router
Route-optimized
communications
Home Agent tunnels packets
to the care-of address
Access Router
(Edge Router)
H
Mobile Node
(LoWPAN Node)
Visited Network (LoWPAN)

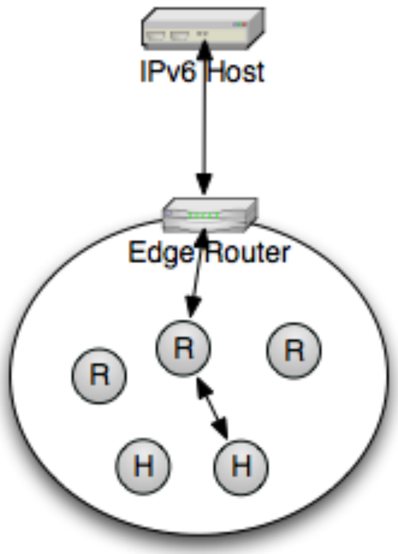
NEMO

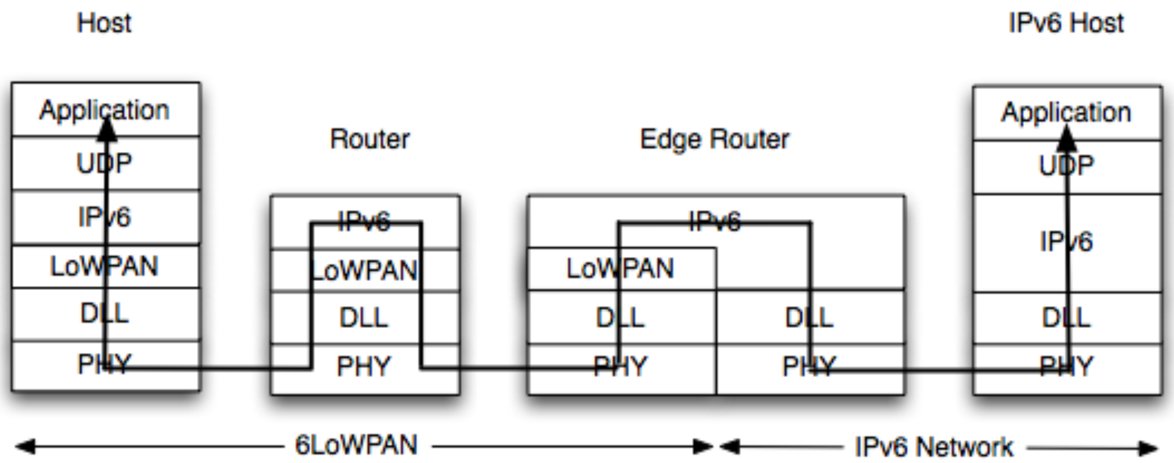


Home Agent
Corresponding Node
Internet
Access Router
Visited Network
Mobile Router
(Edge Router)
H
H
H
H
Mobile Network Nodes
(LoWPAN Nodes)
Mobile Network (LoWPAN)

6LoWPAN Routing

- Here we consider IP routing (at layer 3)
- Routing in a LoWPAN
  - Single-interface routing
  - Flat address space (exact-match)
  - Stub network (no transit routing)





Types of Routing Protocols

- Algorithm classes
  - Distance-vector

    Links are associated with cost, used to find the shortest route. Each router along the path store local next-hop information about its route table.
  - Link-state

    Each node aquires complete information about the network, typically by flooding. Each node calculated a shortest-path tree calculated to each destination.
- Types of Signaling
  - Proactive

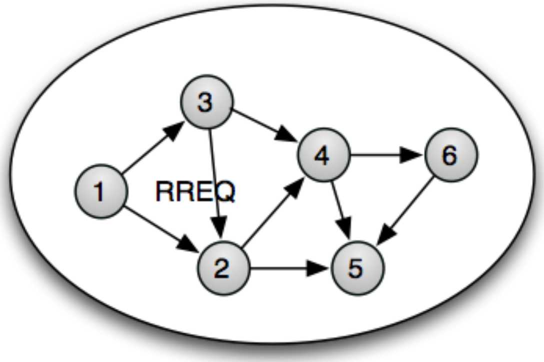
    Routing information aquired before it is needed.
  - Reactive

    Routing information discovered dynamically when needed.
- Route metrics are an important factor

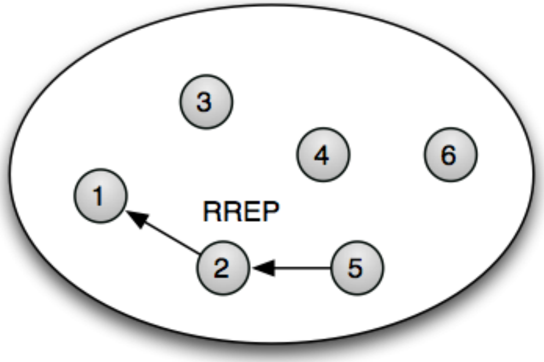
Protocols for 6LoWPAN

- IP is agnostic to the routing protocol used
  - It forwards based on route table entries
- Thus 6LoWPAN is routing protocol agnostic
- Special consideration for routing over LoWPANs
  - Single interface routing, flat topology
  - Low-power and lossy wireless technologies
  - Specific data flows for embedded applications
- MANET protocols useful in some ad-hoc cases
  - e.g. AODV, DYMO
- New IETF working group formed
  - Routing over low-power and lossy networks (ROLL)
  - Deloped specifically for embedded applications

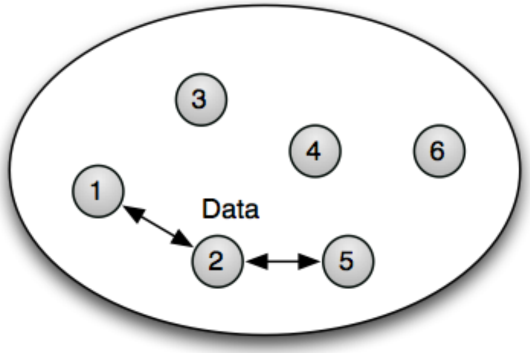
Reactive MANET Protocols



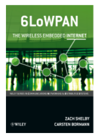
1. RREQ for node 5 broadcast over multiple hops.



2. RREP unicast back to node 1, creates route entries.



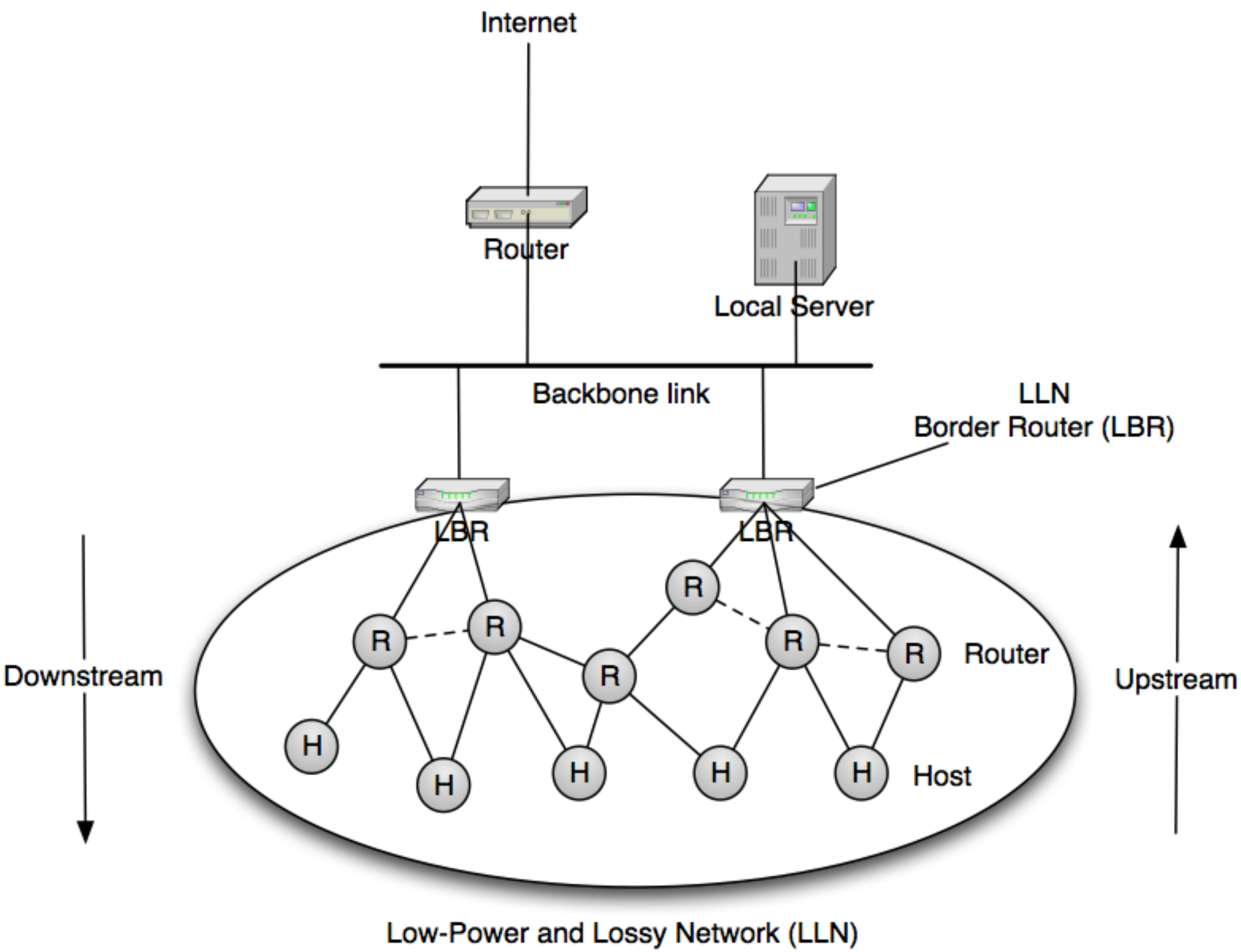
3. Route entries in 1, 2 and 5 enable forwarding.



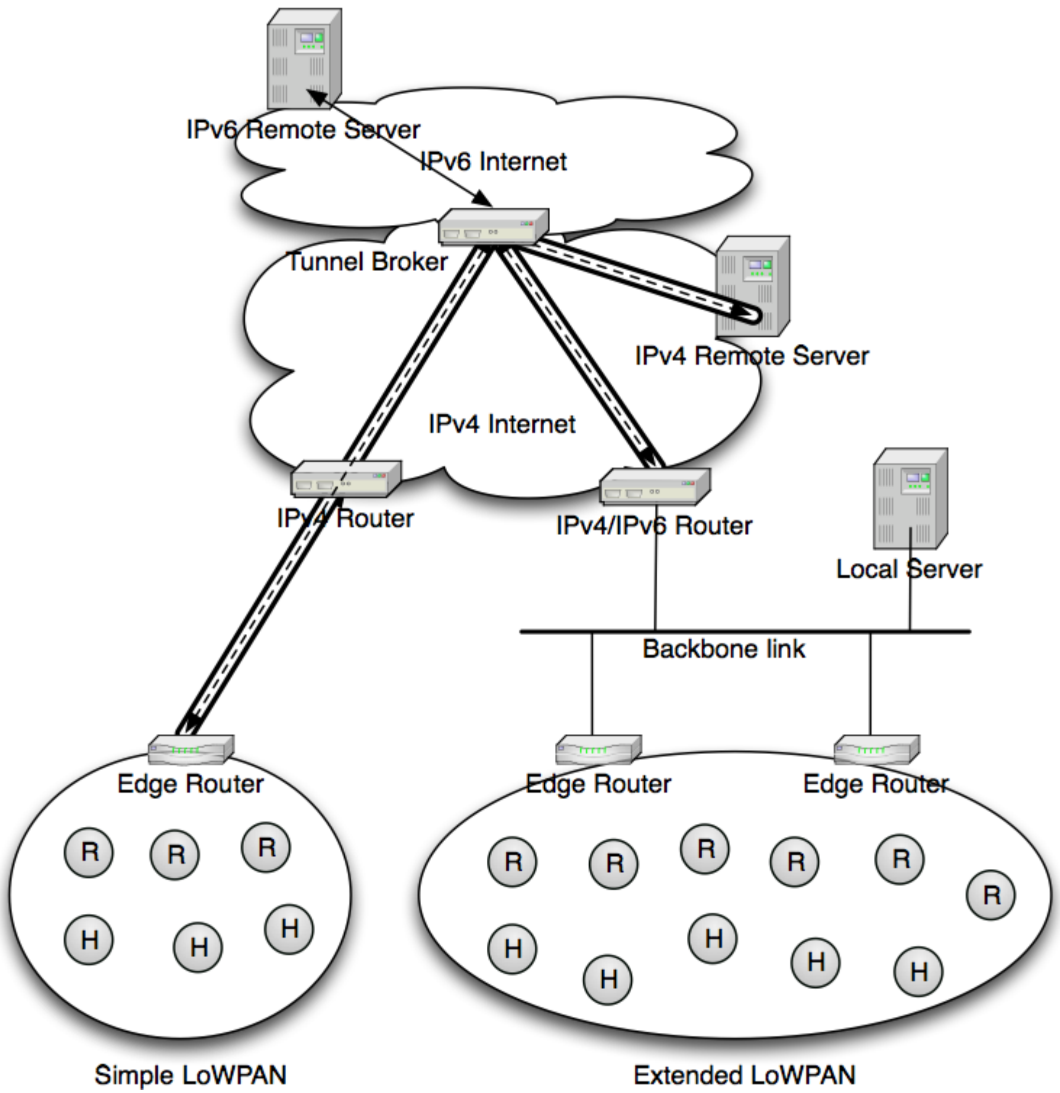
IETF ROLL

- Routing Over Low power and Lossy networks (ROLL)
  - Working group at the IETF
- Standardizing a routing algorithm for embedded apps
- Application specific requirements
  - Home automation
  - Commercial building automation
  - Industrial automation
  - Urban environments
- Analyzed all existing protocols
- Solution must work over IPv6 and 6LoWPAN
- Protocol in-progress called RPL “Ripple”
  - Proactive distance-vector approach
  - See draft-ietf-roll-rpl for detailed information

ROLL RPL “Ripple”



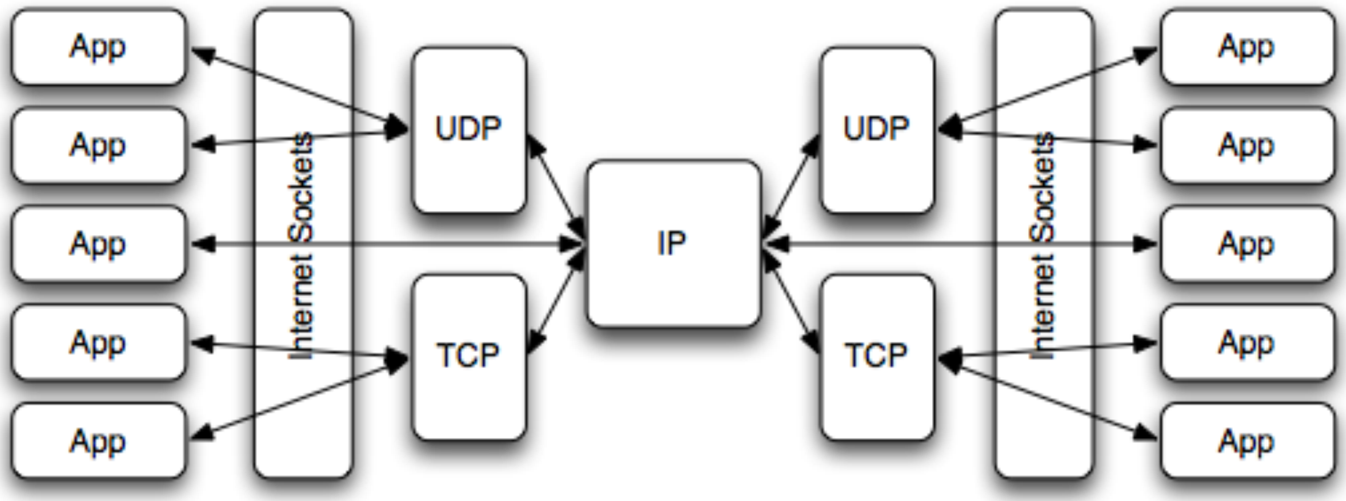
IPv4 Interconnectivity



Application Formats and Protocols

Introduction

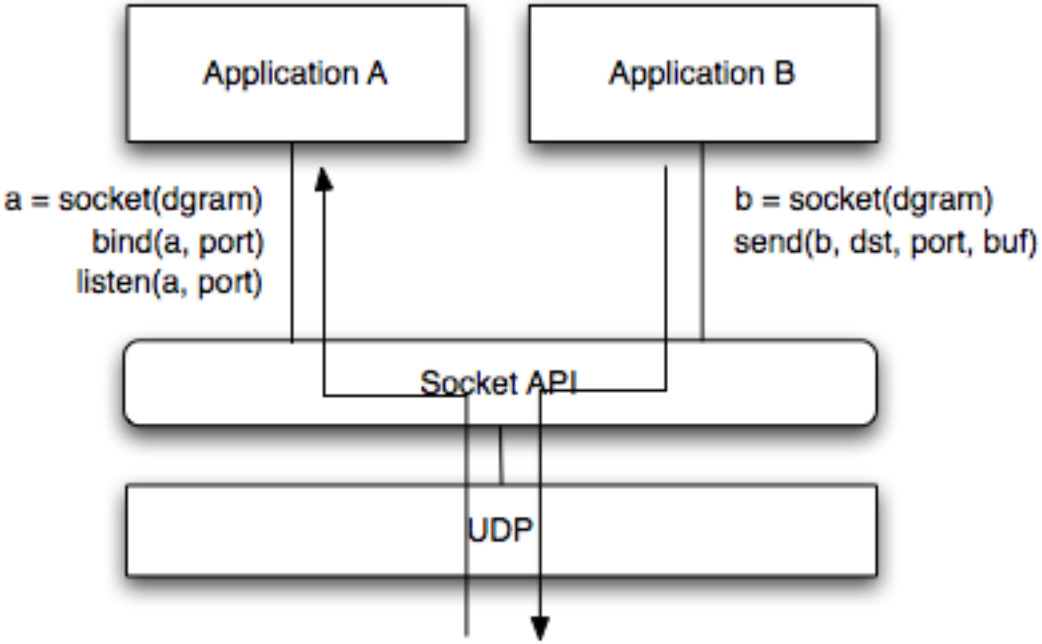
- The processes of applications communicate over IP using an Internet Socket approach
- 6LoWPAN also uses the Internet Socket paradigm
- Application protocols used with 6LoWPAN however have special design and performance requirements



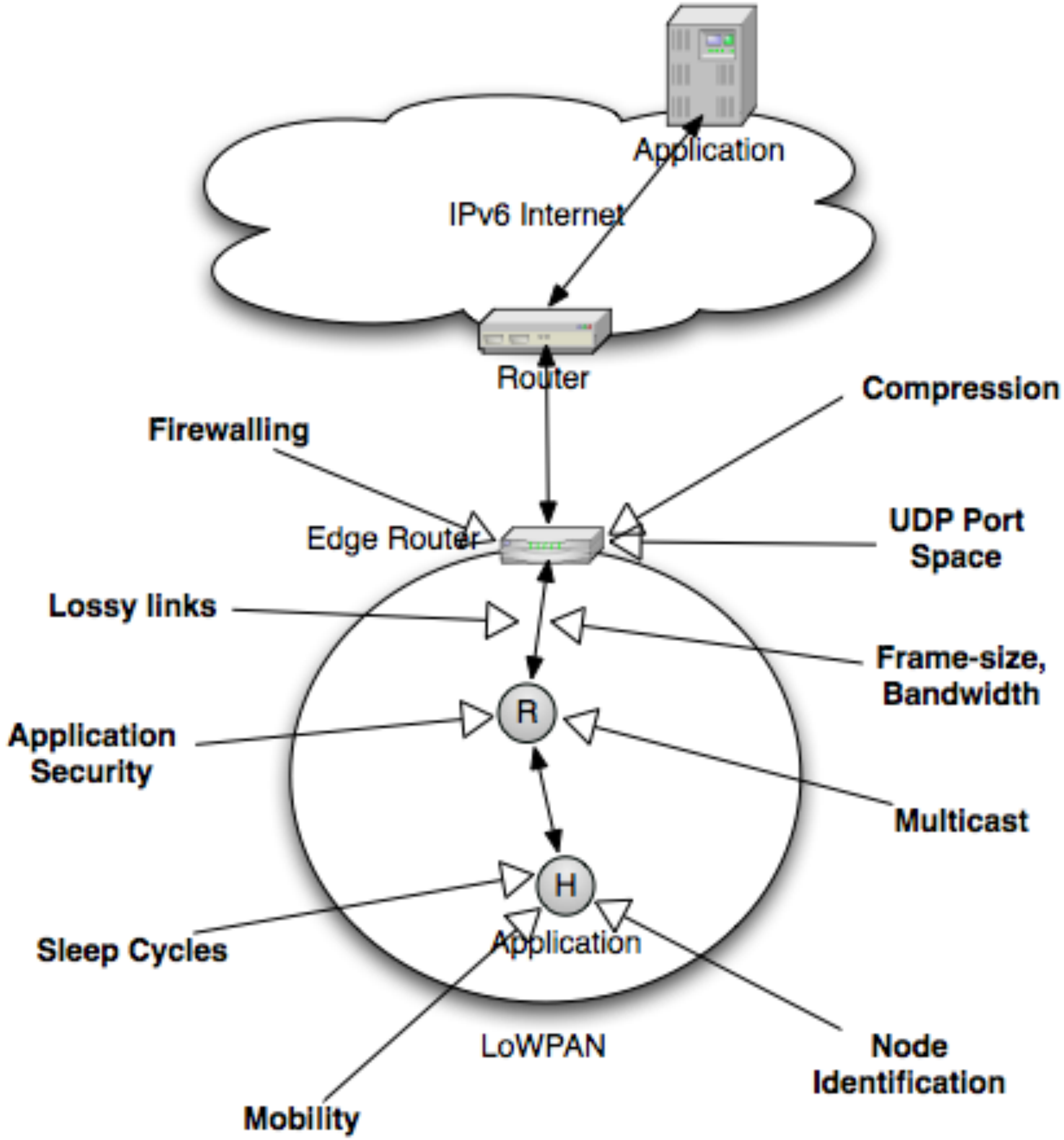
Socket API

- The Socket API provides access to data communications for applications
- Well-known interface for handling data flow and buffer management via socket
- Supports also control messages to protocols
- Commands include:
  - socket, bind, send, read, close etc.
- Examples of Socket APIs
  - Berkeley sockets in *nix systems
  - Mac OSX (Darwin)
  - Contiki uIP (Pseudo socket approach)

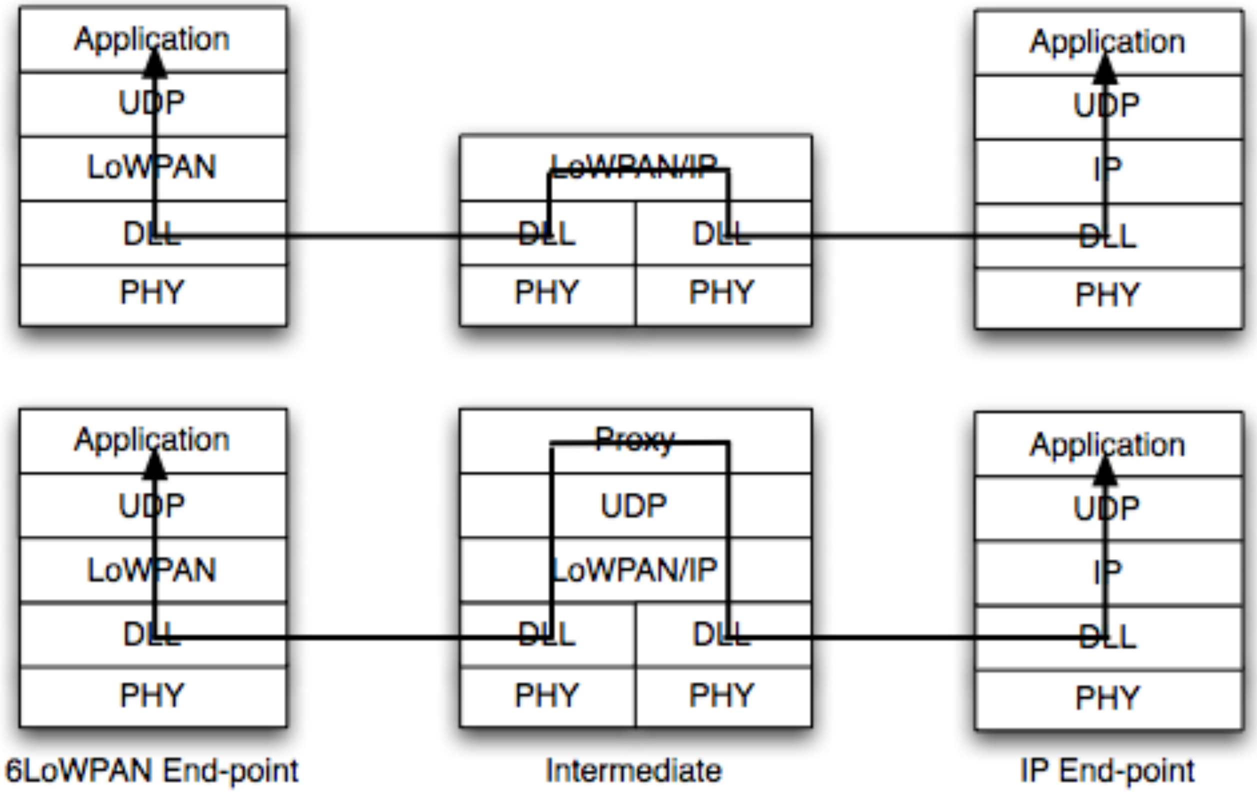
Socket API


Application A
Application B
a = socket(dgram)
bind(a, port)
listen(a, port)
b = socket(dgram)
send(b, dst, port, buf)
Socket API
UDP

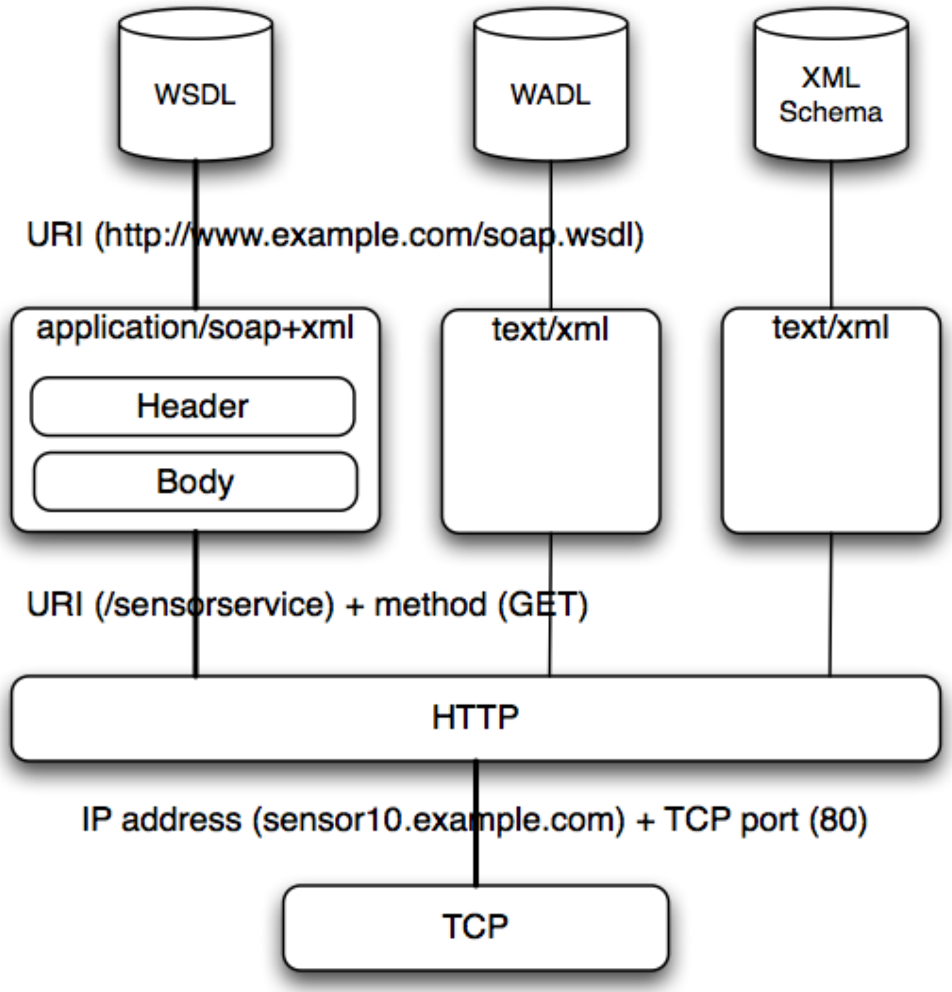
Design Issues



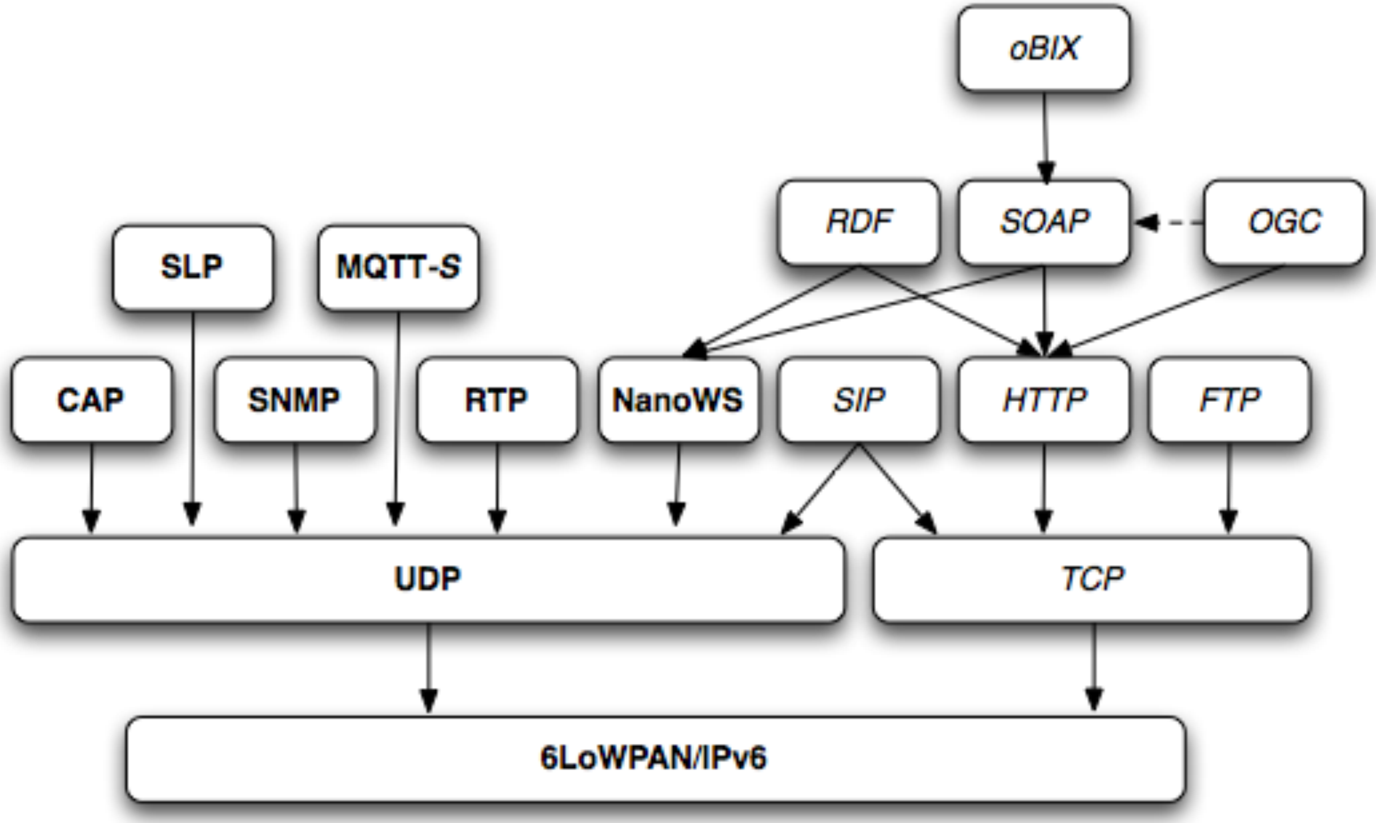
End-to-end Paradigm



Web-service Paradigm

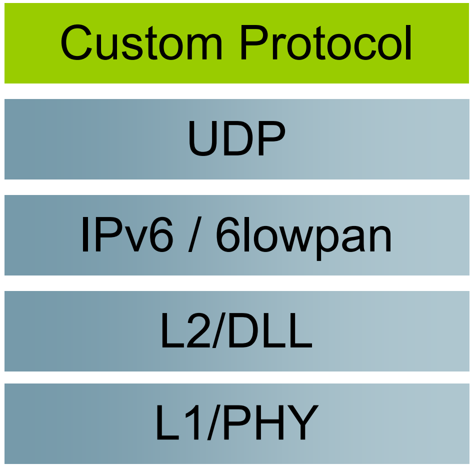


Application Formats and Protocols



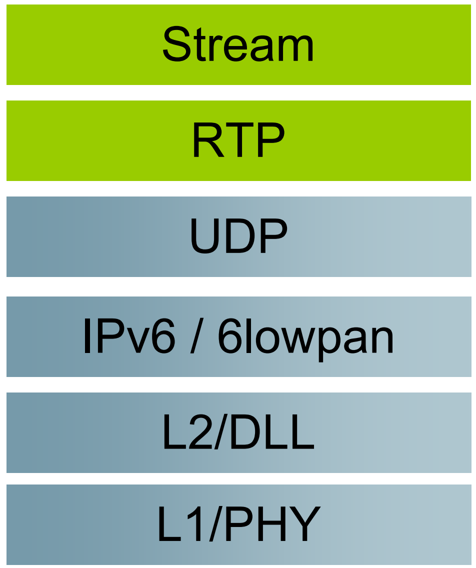
Custom Protocols

- The most common solution today
- Application data typically binary encoded, application specific
- Application protocol uses a specific UDP port, application specific
- As 6LoWPAN is end-to-end IPv6 communications, not a problem
- Advantage:
  - Compact, efficient, security can be integrated, end-to-end
- Disadvantage:
  - Custom server app needed, little re-use, learning curve, interoperability



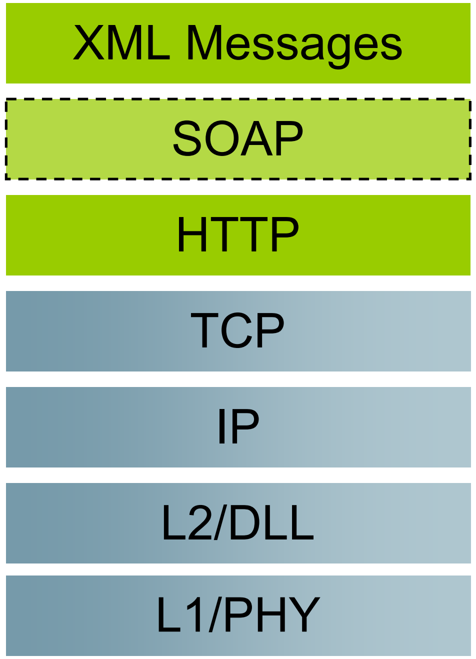
Streaming and RTP

- The correct streaming solution
- For audio or continuous sensor streaming
  - Audio over 802.15.4 needs good codec
- Advantages:
  - RTP can be used over 6LoWPAN
  - Provides end-to-end solution
  - No server modifications needed
  - Jitter control
- Disadvantages:
  - Headers could be more efficient for simple sensor data streaming



XML/HTTP

- De-facto for inter-server communications
- Well-known XML schema important
- All Internet servers speak HTTP/XML
- Useable for RPC, pub/sub and events
- SOAP or REST paradigm
- Advantages:
  - Well known XML schema
  - Formal message sequences
  - Internet-wide support
- Disadvantages:
  - Inefficient, complex
- Solution: Embedded web-services
  - See the IETF 6lowapp effort http://6lowapp.net



Other Application Protocols

- Service Discovery
  - Service Location Protocol (SLP)
  - Device Profile Web Services (DPWS)
- Management
  - Simple Network Mangement Protocol (SNMP)
- M2M Telemetry
  - MQ Telemetry Transport for Sensors (MQTT-S)
- Building Automation
  - BACnet/IP
  - oBIX
- Energy Industry
  - ANSI C12
  - Device Language Message Specification (DLMS)

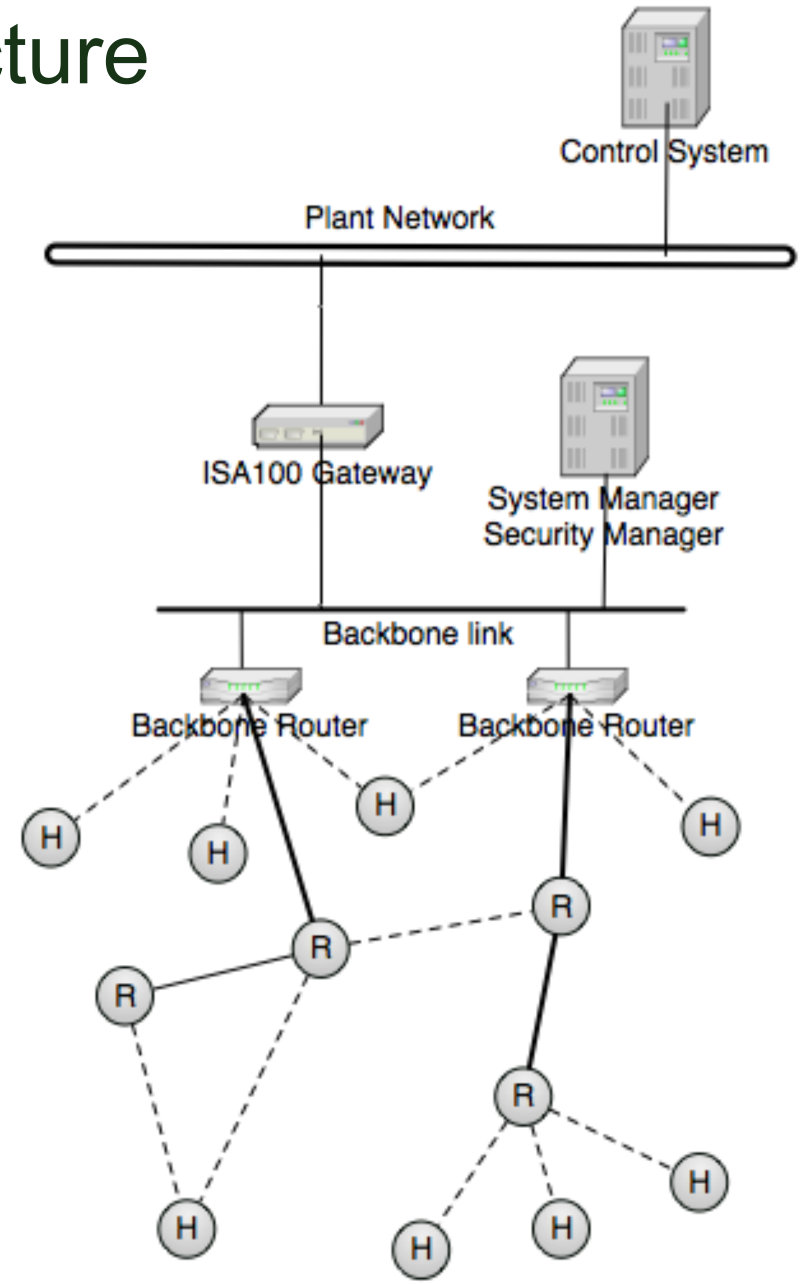
System Examples

ISA100 Industrial Automation

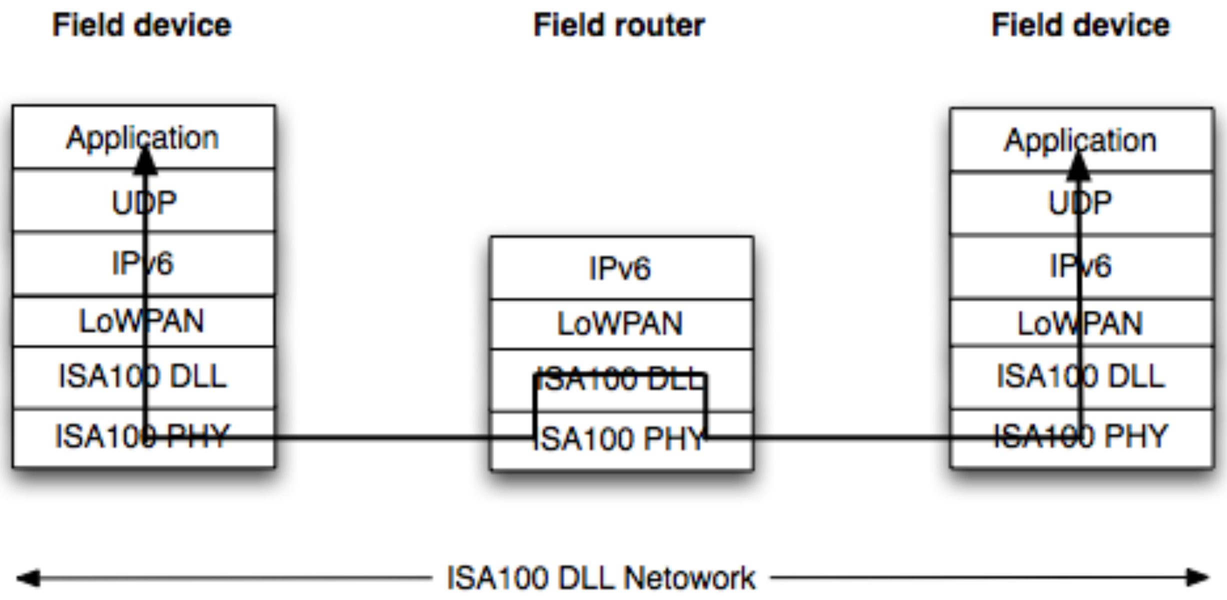
ISA100

- Standard effort from the Instrumentation, Systems, and Automation Society (ISA)
  - Standardization activities accredited by ANSI
- Has been estimated that 55% of industry will support ISA100 in the next few years
- ISA100 group standardizes wireless systems for automation
- ISA100.11a standardization is in progress
  - IEEE 802.15.4-2006 Radio Standard
    - With frequency hopping improvements
  - 6LoWPAN Networking (6LoWPAN, IPv6, UDP)
  - Network gateways, monitoring, deployment, interoperability
  - Defining reliability classes 0 to 5
  - First version of approved standard released in 2009

ISA100 Architecture



ISA100 Forwarding



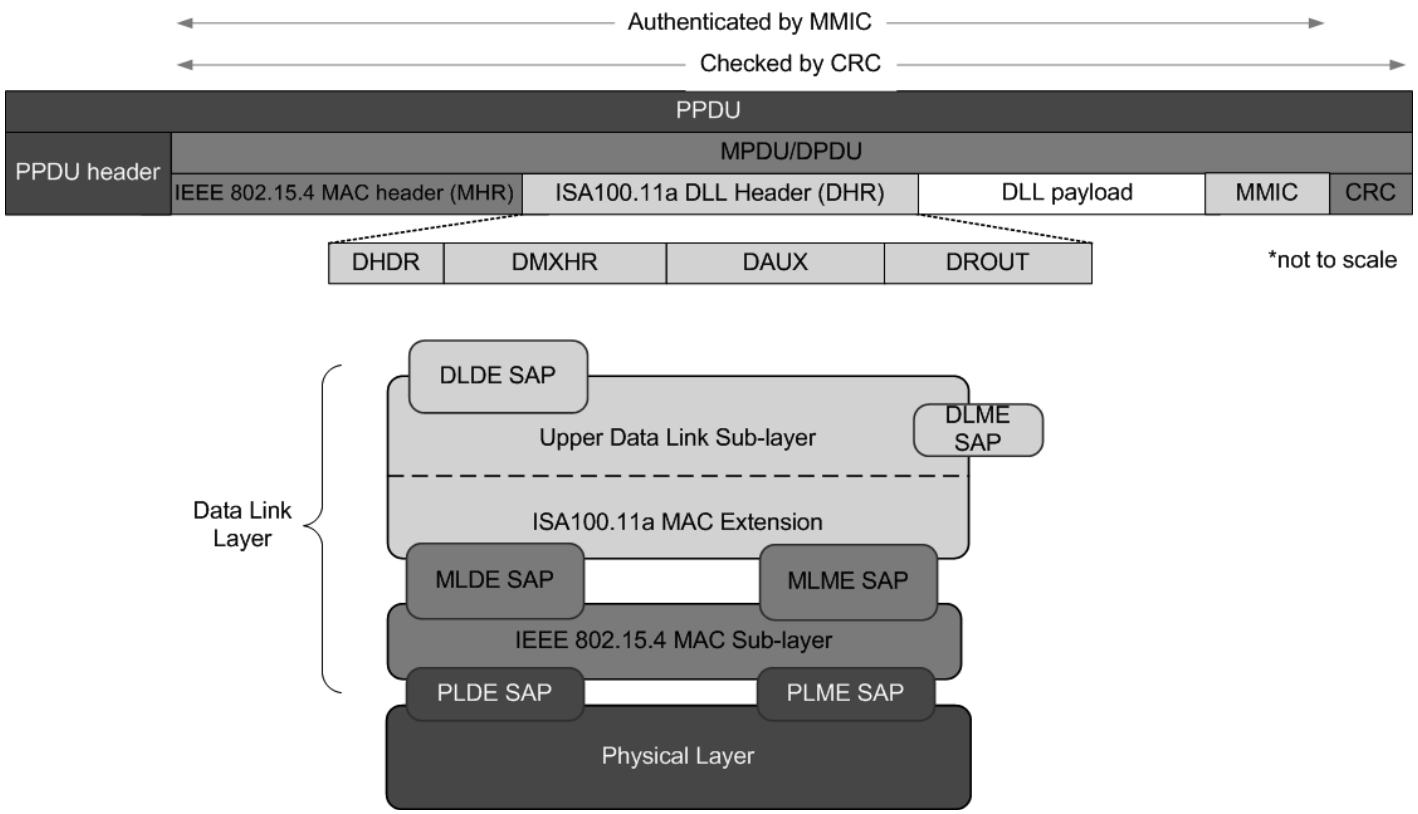
Usage Classes

Safety	Class 0: Emergency action	Always critical	Importance of message timeliness increases →
Control	Class 1: Closed loop regulatory control	Often critical	
	Class 2: Closed loop supervisory control	Usually non-critical	
	Class 3: Open loop control	Human in the loop	
		NOTE Batch levels* 3 & 4 could be class 2, class 1 or even class 0, depending on function *Batch levels as defined by ISA S88; where L3 = unit and L4 = process cell	
Monitoring	Class 4: Alerting	Short-term operational consequence (e.g., event-based maintenance)	
	Class 5: Logging and downloading / uploading	No immediate operational consequence (e.g., history collection, sequence-of-events, preventive maintenance)	

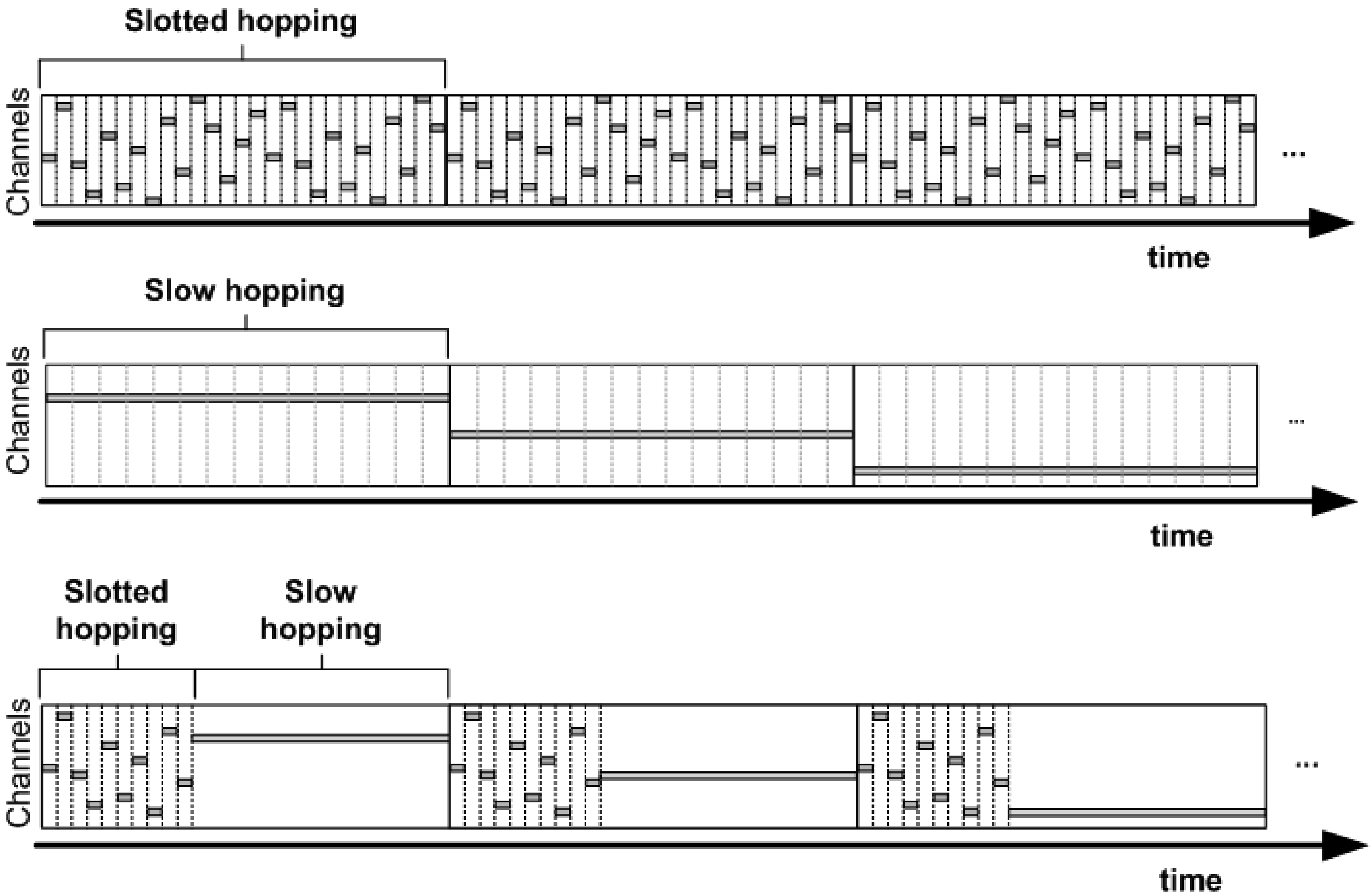
PHY/DLL

- 802.15.4-2006 2.4 GHz used as in standard
  - Except: carrier sensing is optional
- 802.15.4-2006 MAC sub-layer used as in the standard
- ISA100.11a adds MAC features on-top of this
  - Channel hopping
    - Slotted hopping and slow hopping
  - Time coordination
  - No MAC retransmissions
  - No 802.15.4 beacon mode features used
- DLL (mesh under) routing supported
  - Graph and source routing

PHY/DLL


Authenticated by MMIC
Checked by CRC
PPDU
PPDU header
MPDU/DPDU
IEEE 802.15.4 MAC header (MHR)
ISA100.11a DLL Header (DHR)
DLL payload
MMIC
CRC
DHDR
DMXHR
DAUX
DROUT
*not to scale
Data Link Layer
DLDE SAP
Upper Data Link Sub-layer
DLME SAP
ISA100.11a MAC Extension
MLDE SAP
MLME SAP
IEEE 802.15.4 MAC Sub-layer
PLDE SAP
PLME SAP
Physical Layer

Hopping



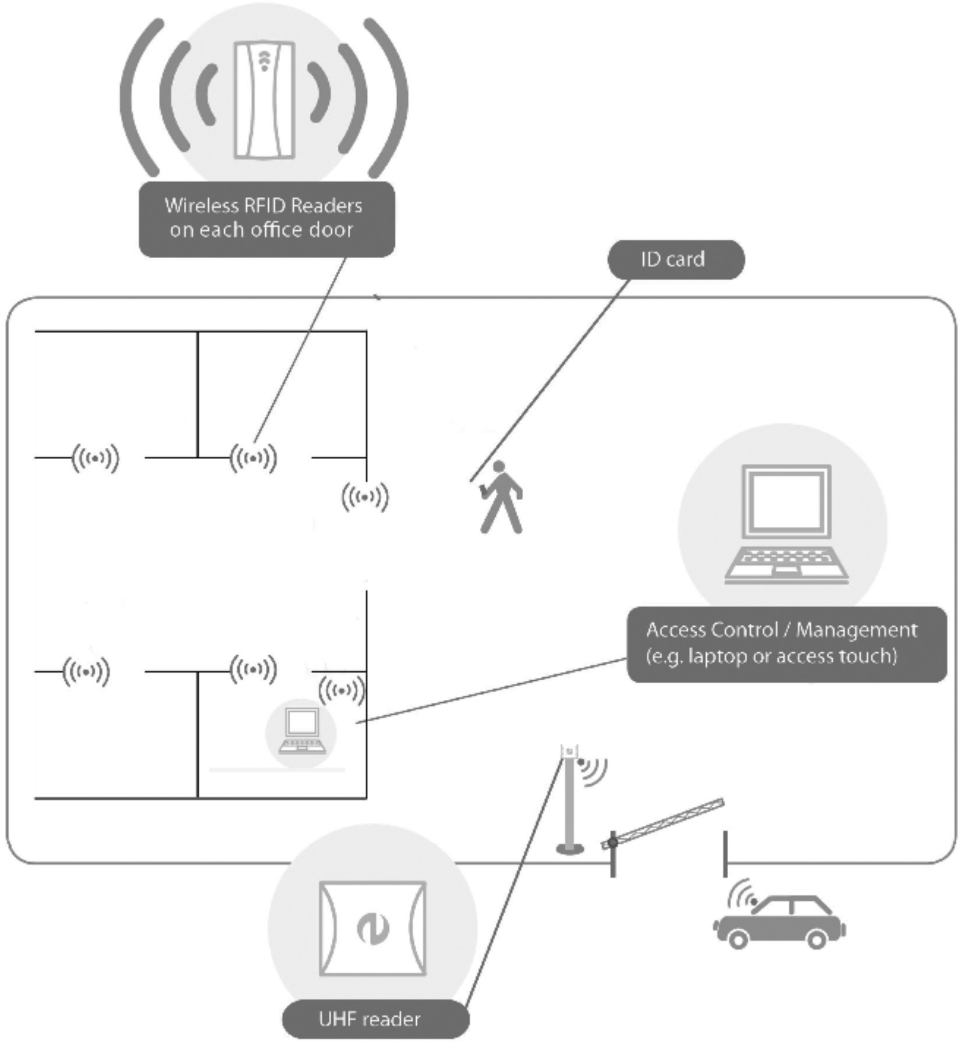
Slotted hopping
Channels
...
time
Slow hopping
Channels
...
time
Slotted hopping
Slow hopping
Channels
...
time

Wireless RFID Infrastructure

Wireless RFID Infrastructure

- Access control is an important part of building automation
- Idesco is a Finnish RFID system provider
  - http://www.idesco.fi
- Idesco Cardea System
  - World's first wireless infrastructure RFID access control system
  - 6LoWPAN networking between RFID components
- System components
  - Idesco Cardea readers
  - Idesco Cardea door control unit
  - Idesco Cardea control unit and Access Touch
- Benefits of using 6LoWPAN
  - Significant reduction in installation time and cost
  - Flexibility and use in temporary installations
  - Makes RFID access control practical for small installations

Wireless RFID Infrastructure



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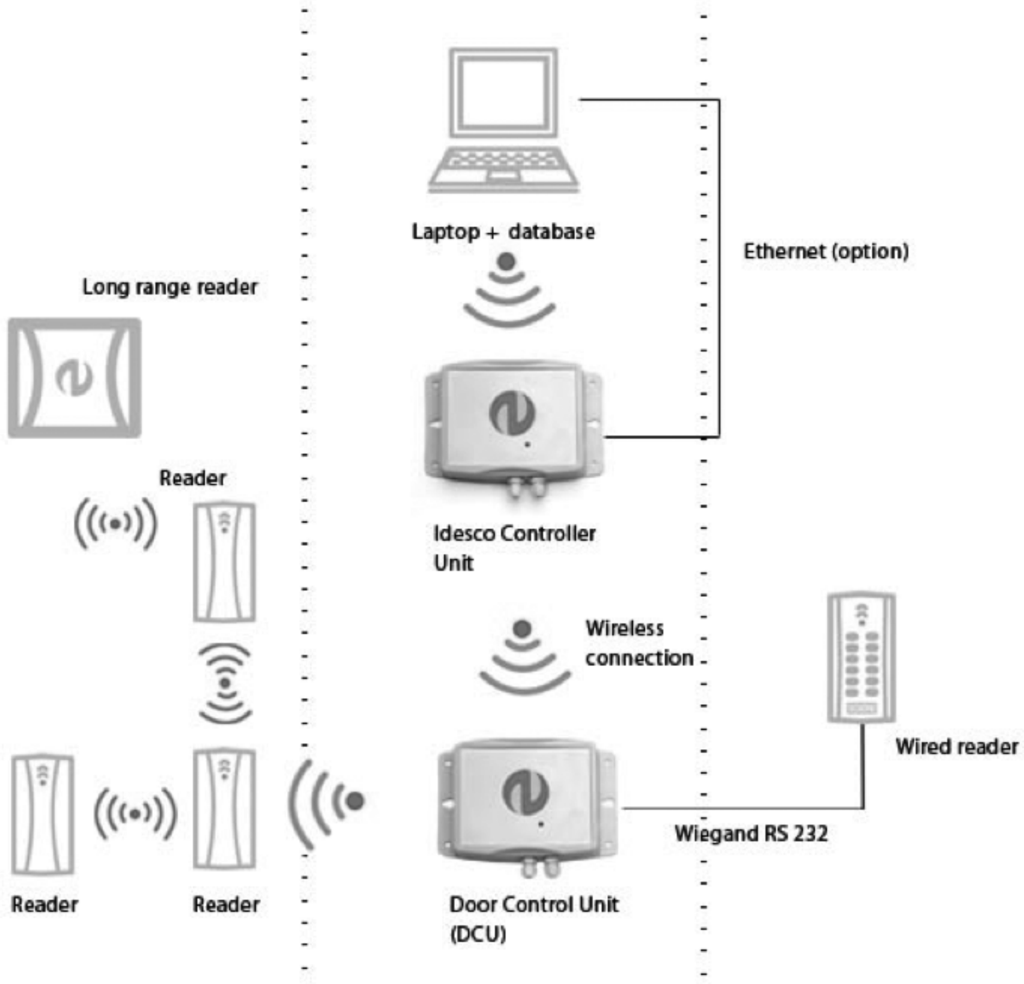
Wireless RFID Infrastructure



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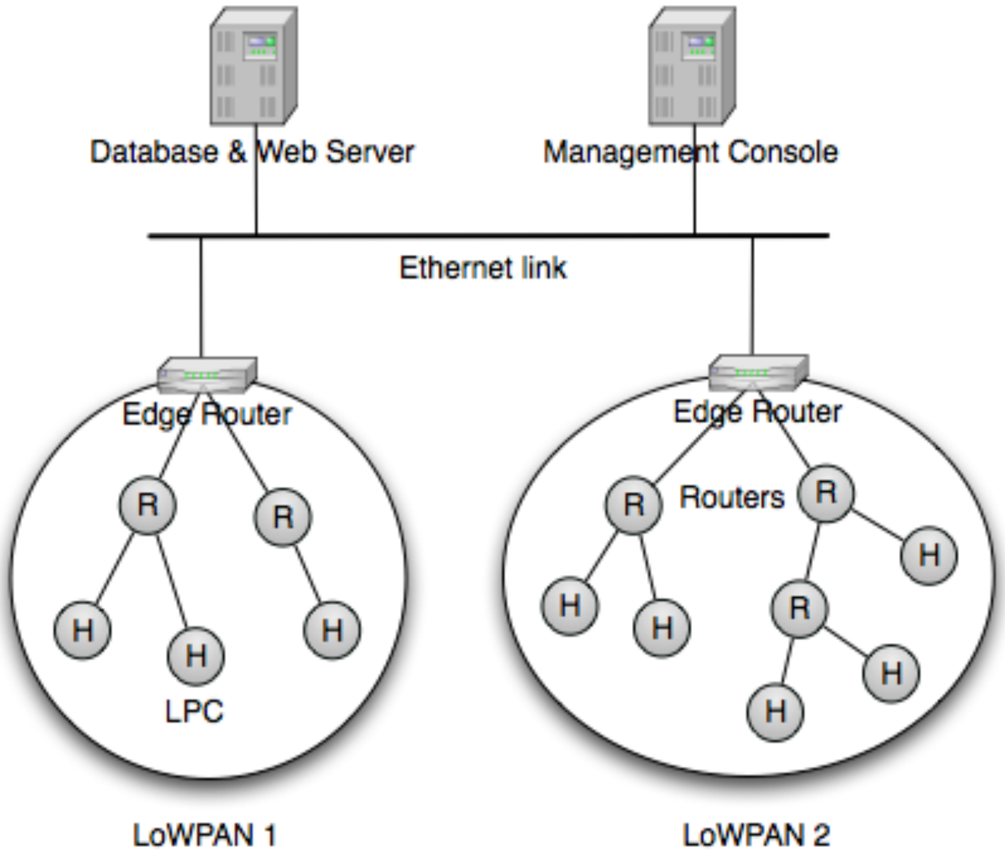
Building Energy Savings

Building Energy Savings

- Energy savings is important in commercial buildings
  - 52% of electricity consumption in the UK
  - UK businesses waste up to 30% of energy purchased
- LessTricity projects aims at this problem
  - Consortium of companies in property management, building design, and management software
  - Based on 6LoWPAN technology from Jennic Ltd.
- Centralized mangement solution
  - Eliminate the wasteful use of electricity in buildings
- System architecture
  - LessTricity power controllers - *measure consumption*
  - LessTricity network interface - *Ethernet router*
  - Link layer mesh, 6LoWPAN and Jennic SNAP protocol

Building Energy Savings



LessTricity Application	
SNAP	
UDP	ICMPv6
IPv6 with 6LoWPAN	
JenNet Mesh Layer	
IEEE 802.15.4