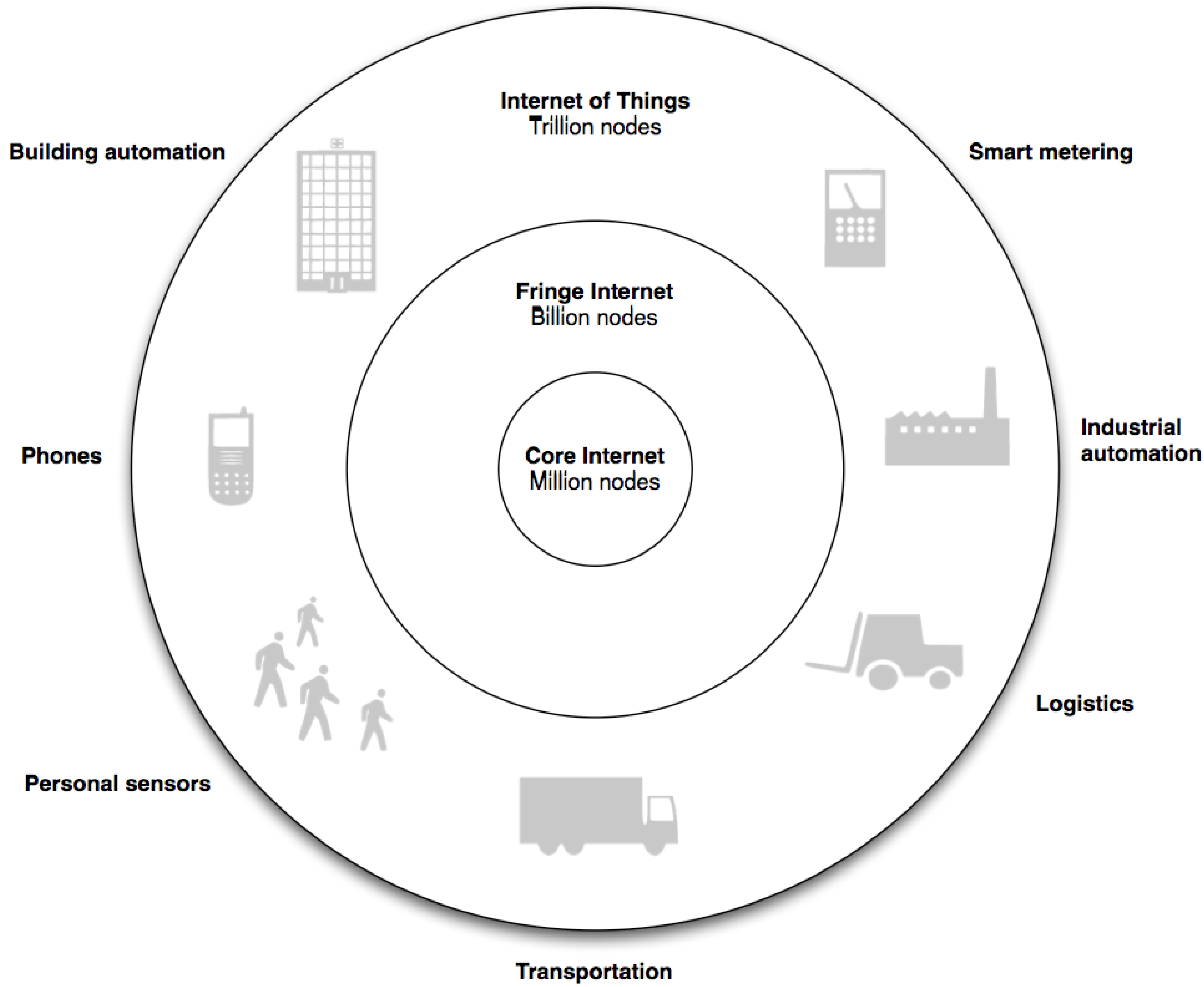
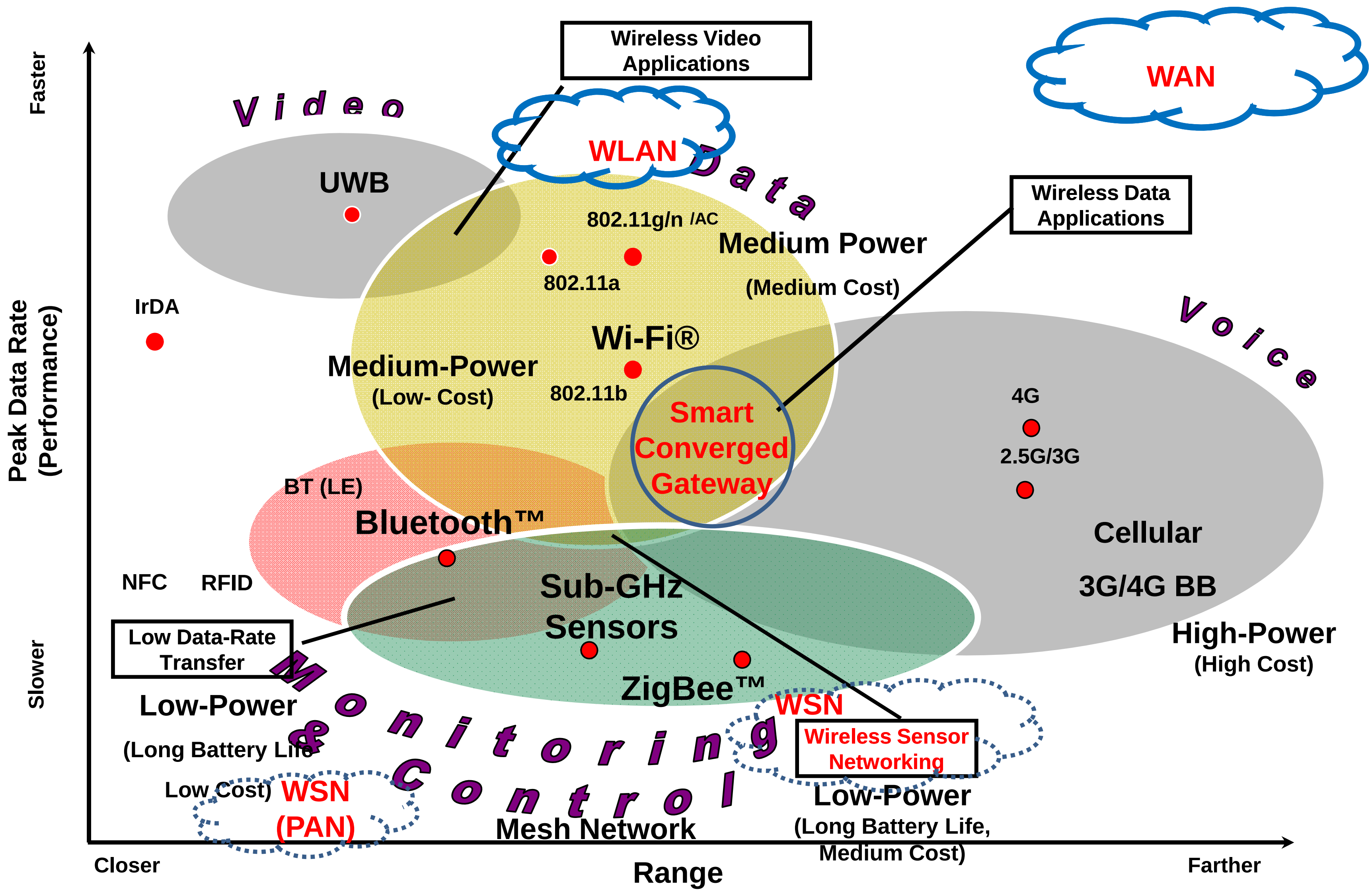


Internet of Things
Trillion nodes
Fringe Internet
Billion nodes
Core Internet
Million nodes
Building automation
Smart metering
Phones
Industrial automation
Personal sensors
Logistics
Transportation

NO!

RF Wireless Data Rates & Ranges

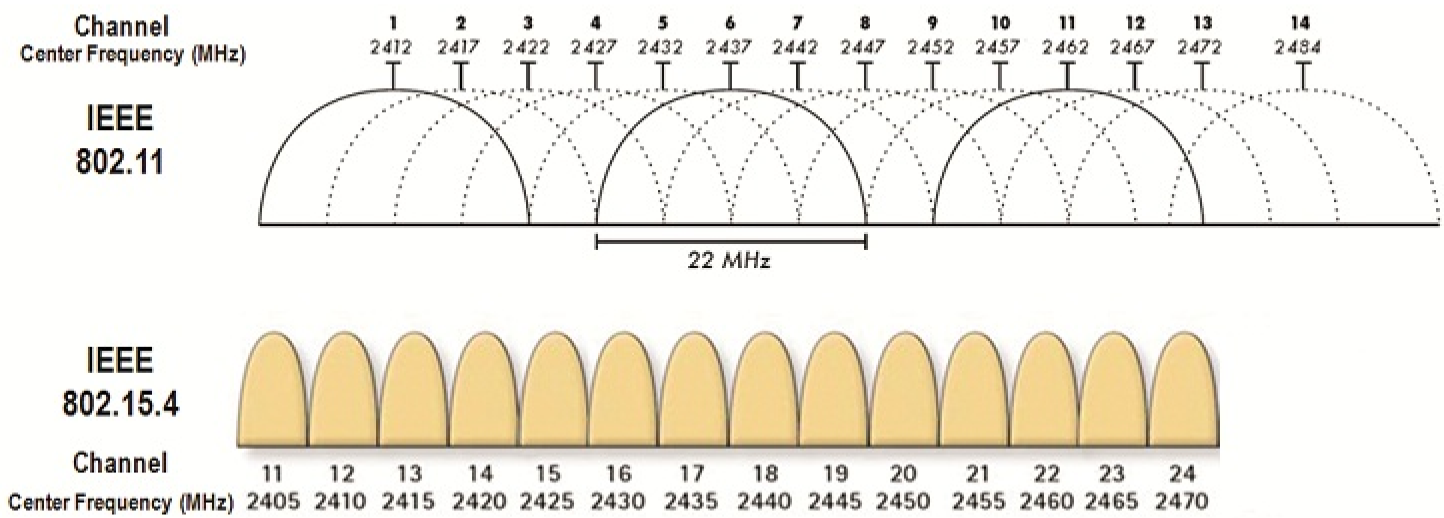


RF Radios Communication Technologies

Communication Technologies

	NFC	RFID	Blue-tooth®	Blue-tooth® LE	ANT	Proprietery (Sub-GHz & 2.4 GHz)	Wi-Fi®	ZigBee®	Z-wave	KNX	Wireless HART	6LoWPAN	WiMAX	2.5–3.5 G
Network	PAN	PAN	PAN	PAN	PAN	LAN	LAN	LAN	LAN	LAN	LAN	LAN	MAN	WAN
Topology	P2P	P2P	Star	Star	P2P, Star, Tree Mesh	Star, Mesh	Star	Mesh, Star, Tree	Mesh	Mesh, Star, Tree	Mesh, Star	Mesh, Star	Mesh	Mesh
Power	Very Low	Very Low	Low	Very Low	Very Low	Very Low to Low	Low-High	Very Low	Very Low	Very Low	Very Low	Very Low	High	High
Speed	400 Kbs	400 Kbs	700 kbs	1 Mbs	1 Mbs	250 kbs	11-100 Mbs	250 kbs	40 Kbs	1.2 Kbps	250 kbs	250 Kbs	11-100 Mbs	1.8-7.2 Mbs
Range	<10 cm	<3 m	<30 m	5-10 m	1-30 m	10-70 m	4-20 m	10-300 m	30 m	800 m	200 m	800 m (Sub-GHz)	50 km	Cellular network
Application	Pay, get access, share, initiate service, easy setup	Item tracking	Network for data exchange, headset	Health and fitness	Sports and fitness	Point to point connectivity	Internet, multimedia	Sensor networks, building and industrial automation	Residential lighting and automation	Building automation	Industrial sensing networks	Senor networks, building and industrial automation	Metro area broadband Internet connectivity	Cellular phones and telemetry
Cost Adder	Low	Low	Low	Low	Low	Medium	Medium	Medium	Low	Medium	Medium	Medium	High	High

IEEE 802.15.4



Channel
Center Frequency (MHz)
1 2 3 4 5 6 7 8 9 10 11 12 13 14
2412 2417 2422 2427 2432 2437 2442 2447 2452 2457 2462 2467 2472 2484
IEEE
802.11
22 MHz
IEEE
802.15.4
Channel
Center Frequency (MHz)
11 12 13 14 15 16 17 18 19 20 21 22 23 24
2405 2410 2415 2420 2425 2430 2435 2440 2445 2450 2455 2460 2465 2470

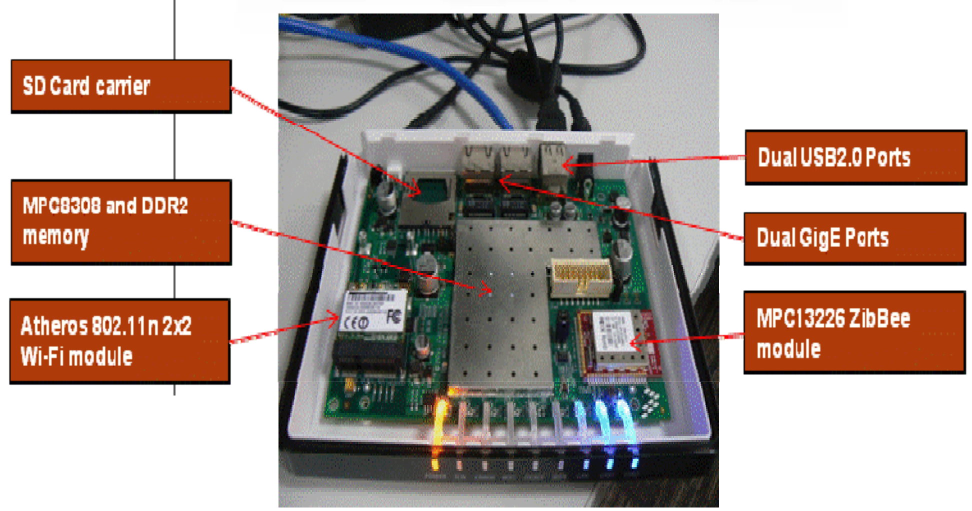
Networked Smart Gateway (MPC8308NSG)

- **Converged Architecture**
  - Wireless media gateway
  - Home security & safety surveillance
  - Smart energy home automation
  - Health monitoring & management

- **Seamless Wireless Connectivity (TCP/IP, 802.11n, ZigBee)**
  - Smart metering connectivity via SE 1.0 or MBus
  - Smart appliance management via ZigBee HA1.0
  - Anytime/Anywhere access via internet connected devices

- **Integration of four essential software stacks**
  - TCP/IP - Broadband WAN/LAN connectivity
  - ZigBee Home Automation 1.0 Profile
  - ZigBee Smart Energy 1.0 Profile
  - Web-based GUI (Java) for Ease of Use

- **Fully ready for Mass Production NOW**
  - Freescale owned hardware & software
  - Solid hardware partnerships
  - Several ODMs are engaged
  - Traction with several consumer & utility OEMs
  - Branding, value and eCommerce enabling platform



The Book

6LoWPAN: The Wireless Embedded Internet

by Zach Shelby, Carsten Bormann

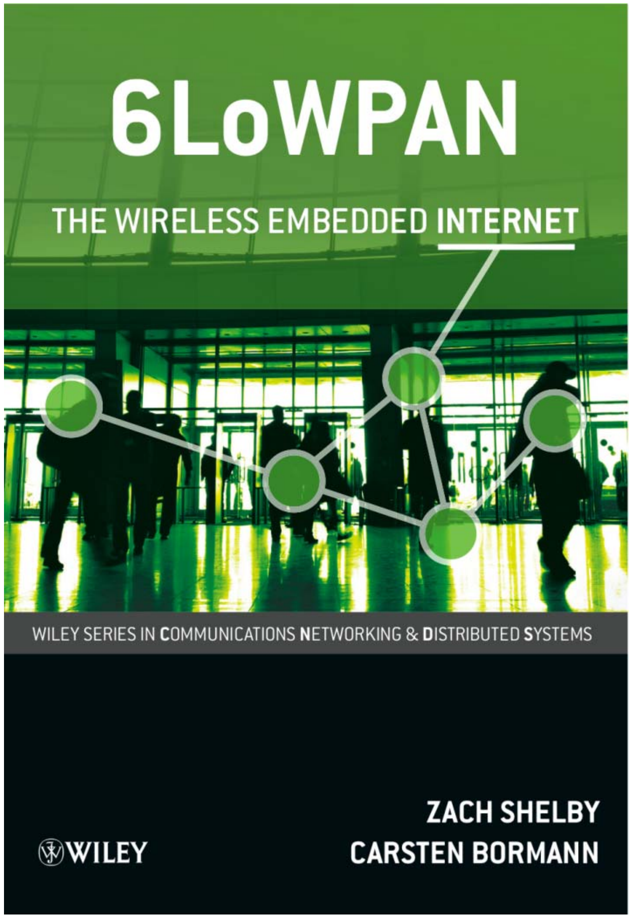
Length: 254 pages

Publisher: John Wiley & Sons

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

http://6lowpan.net

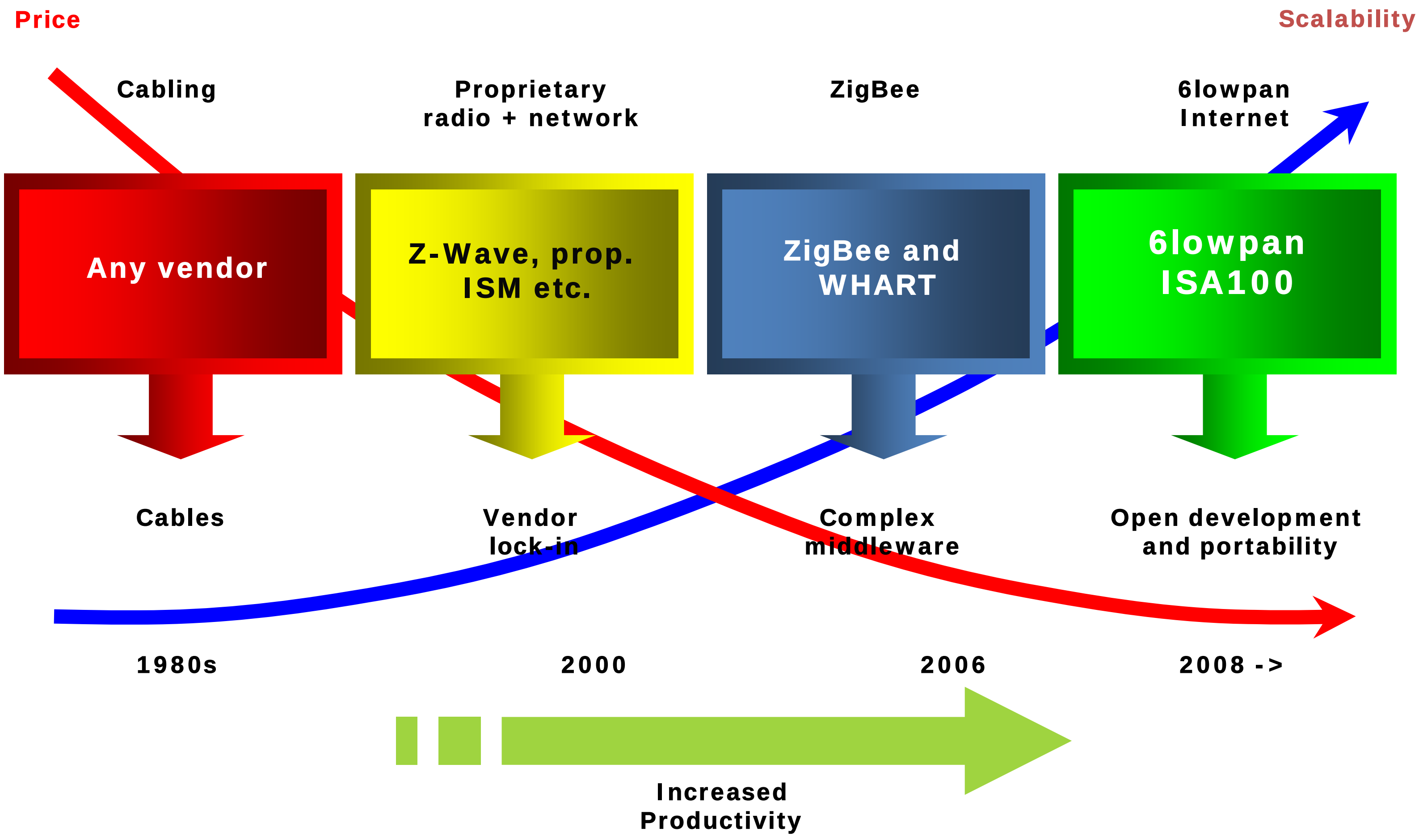
Companion web-site with blog, full companion course slides and exercises



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

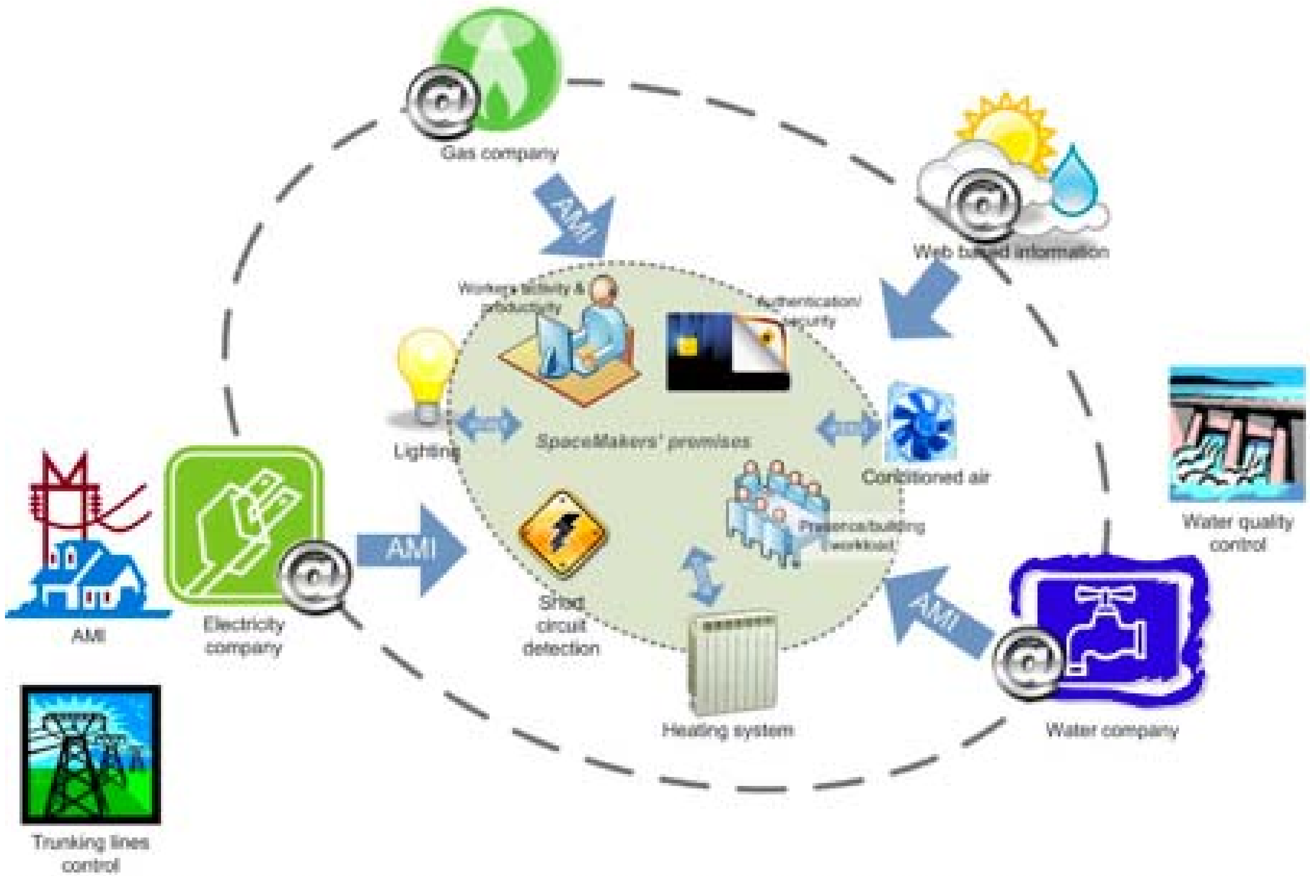
Evolution of Wireless Sensor Networks



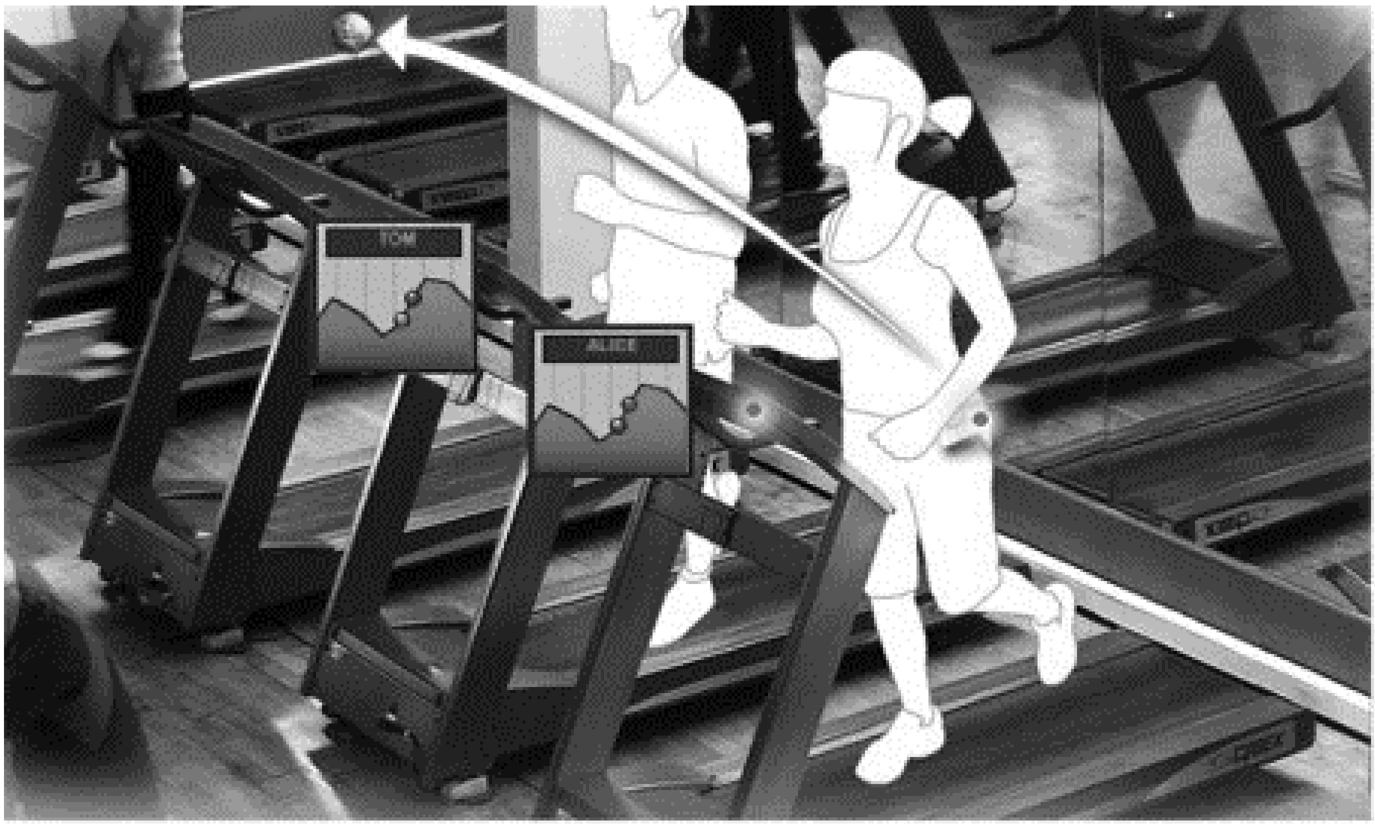
6LoWPAN Applications

- 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

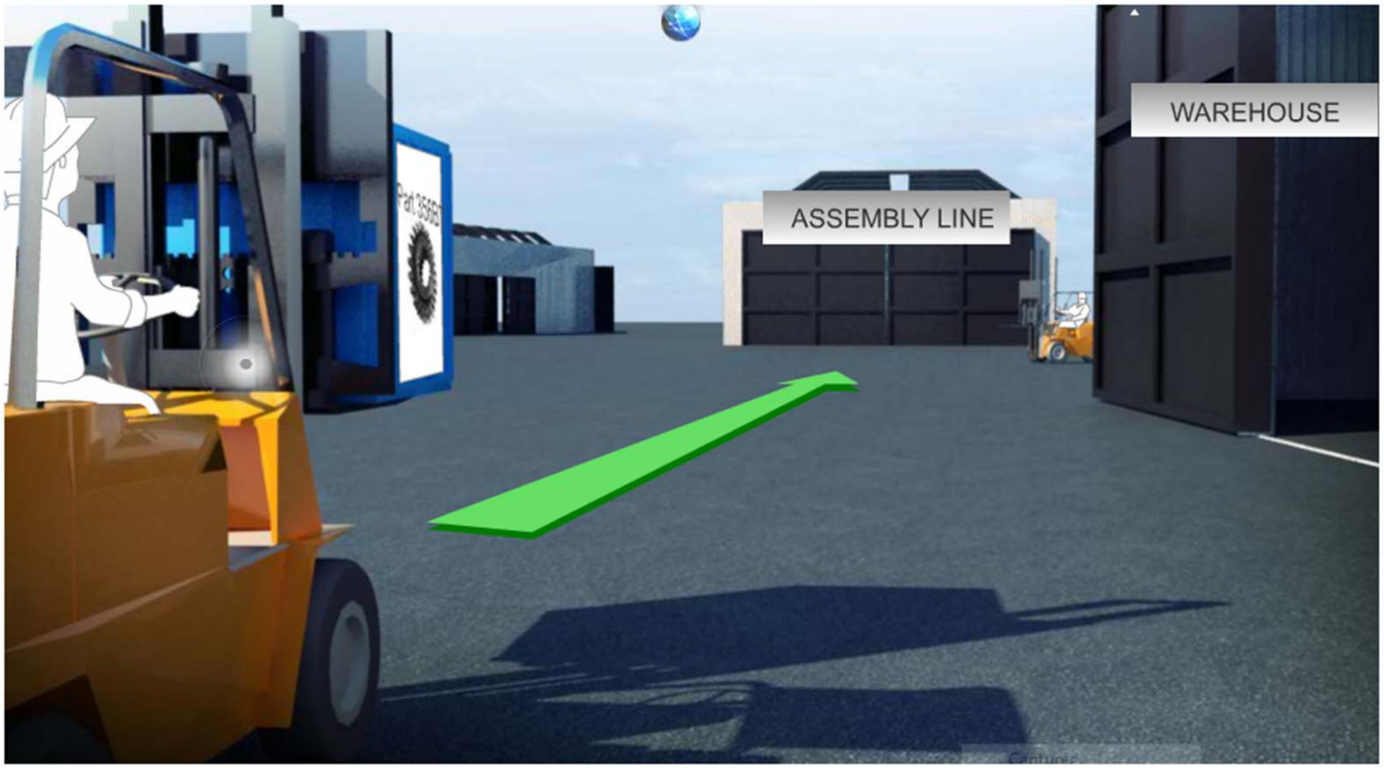
Facility Management



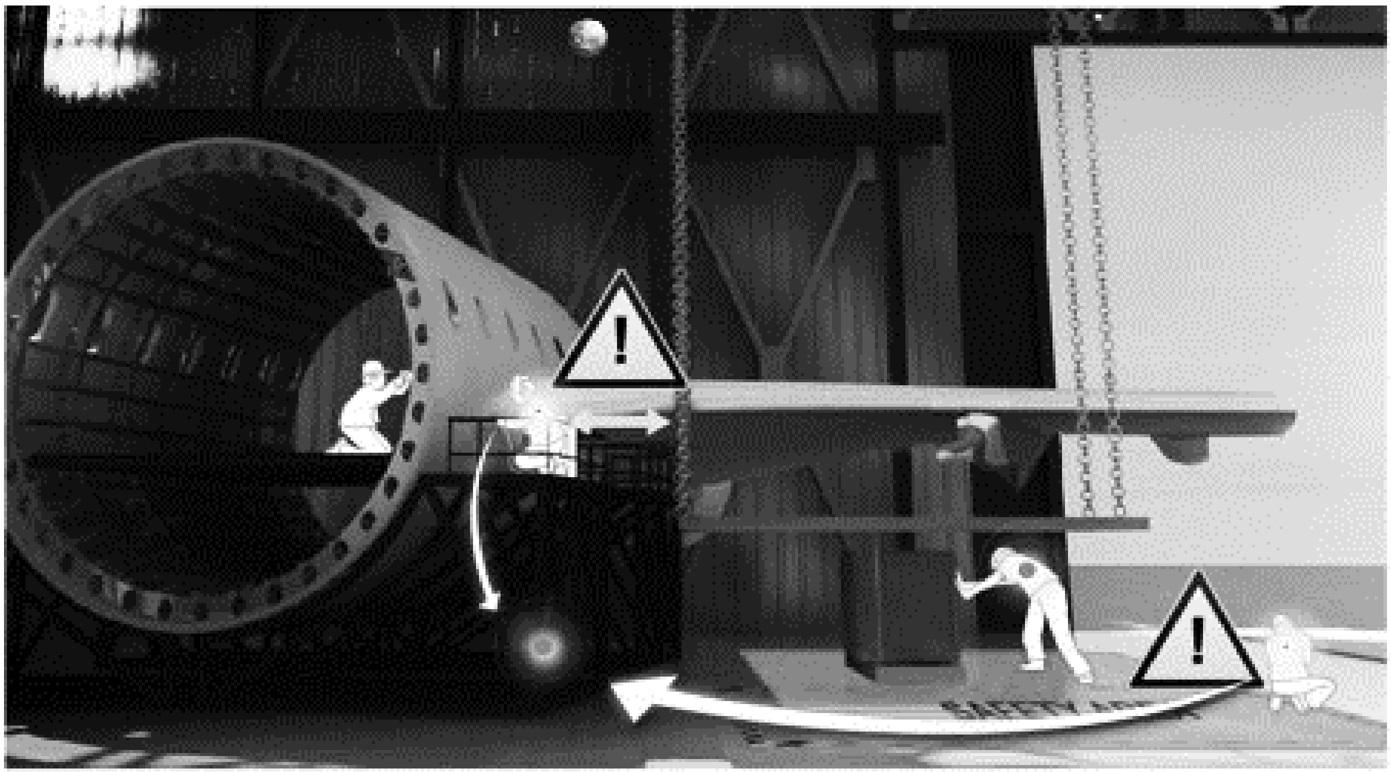
Fitness



Asset Management



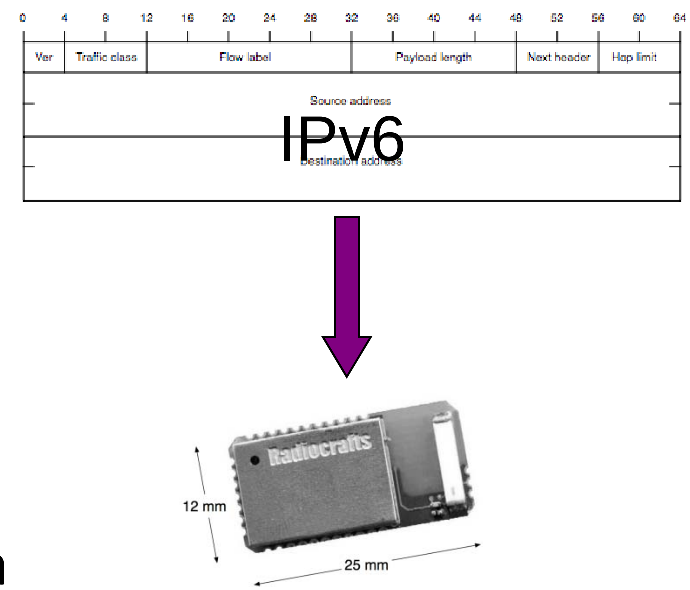
Industrial Automation



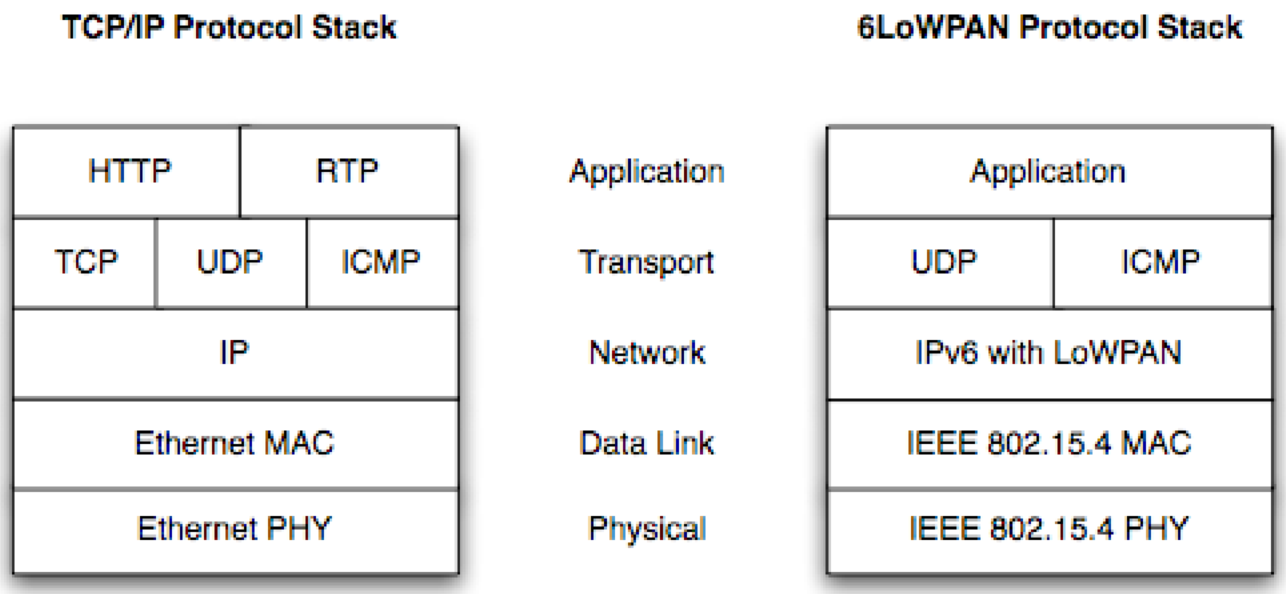
Introduction to 6LoWPAN

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

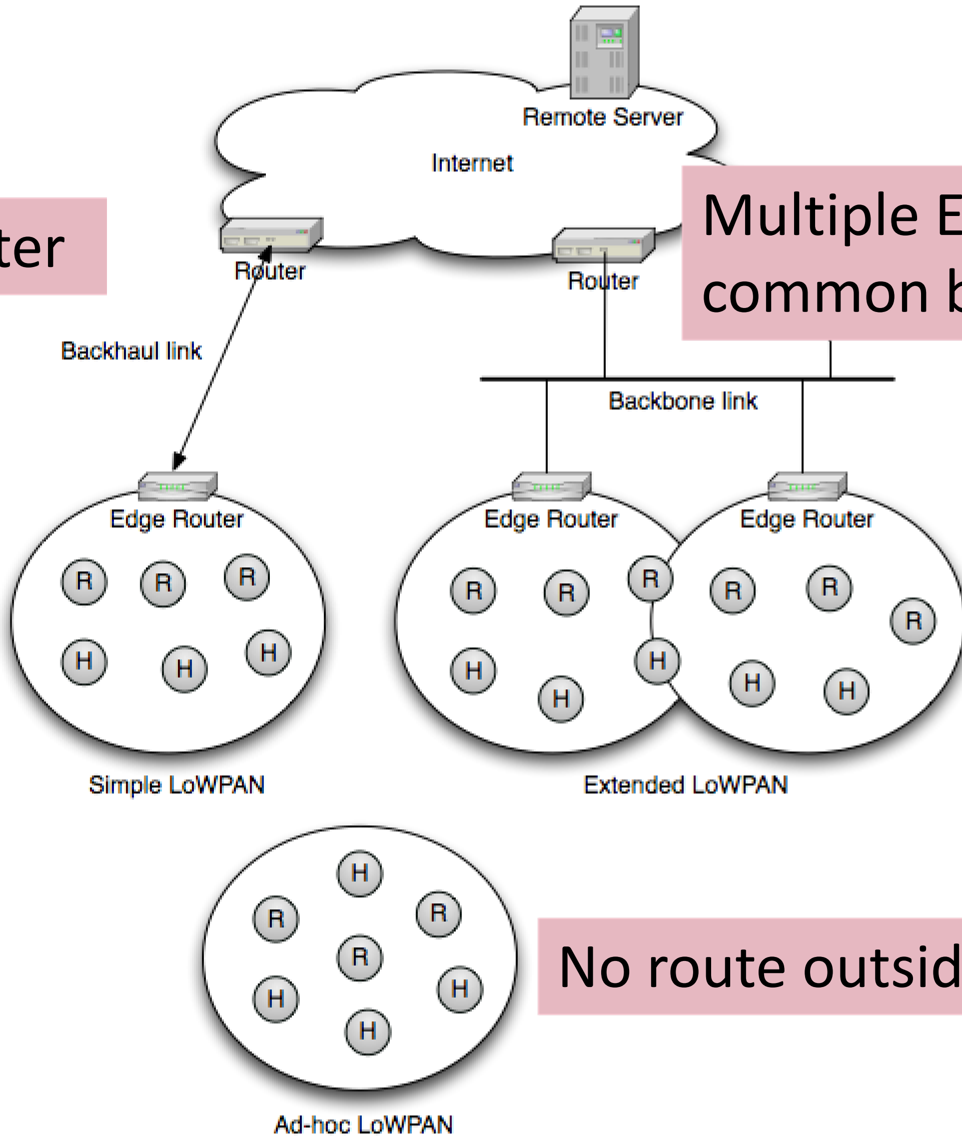


Features

- Support for 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 (ND)
- 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)

6LoWPAN Architecture

Single Edge Router



Multiple Edge Routers with common backbone link

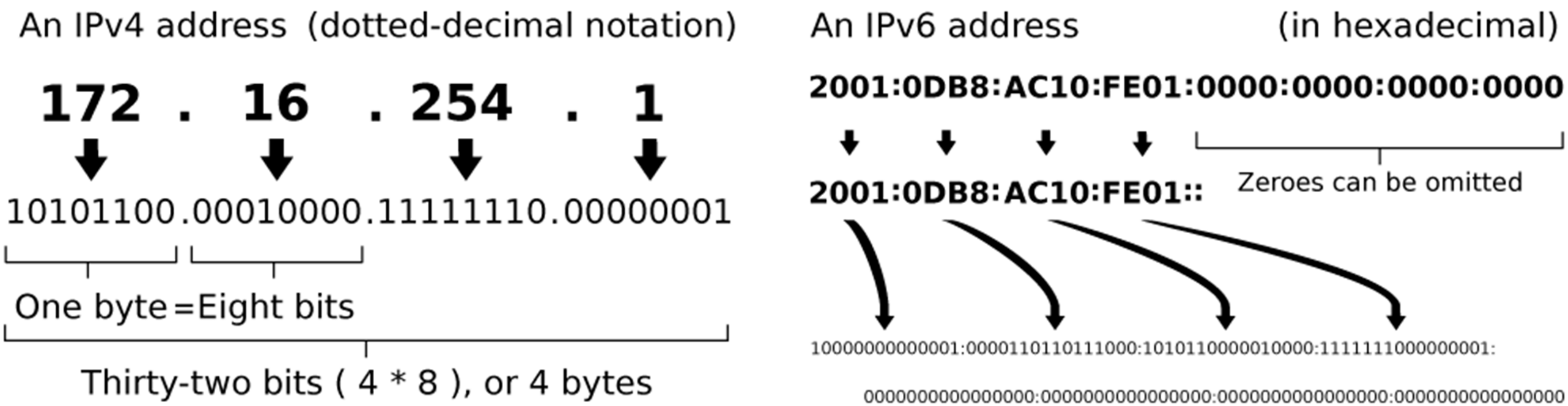
No route outside the LoWPAN

Internet Protocol v6

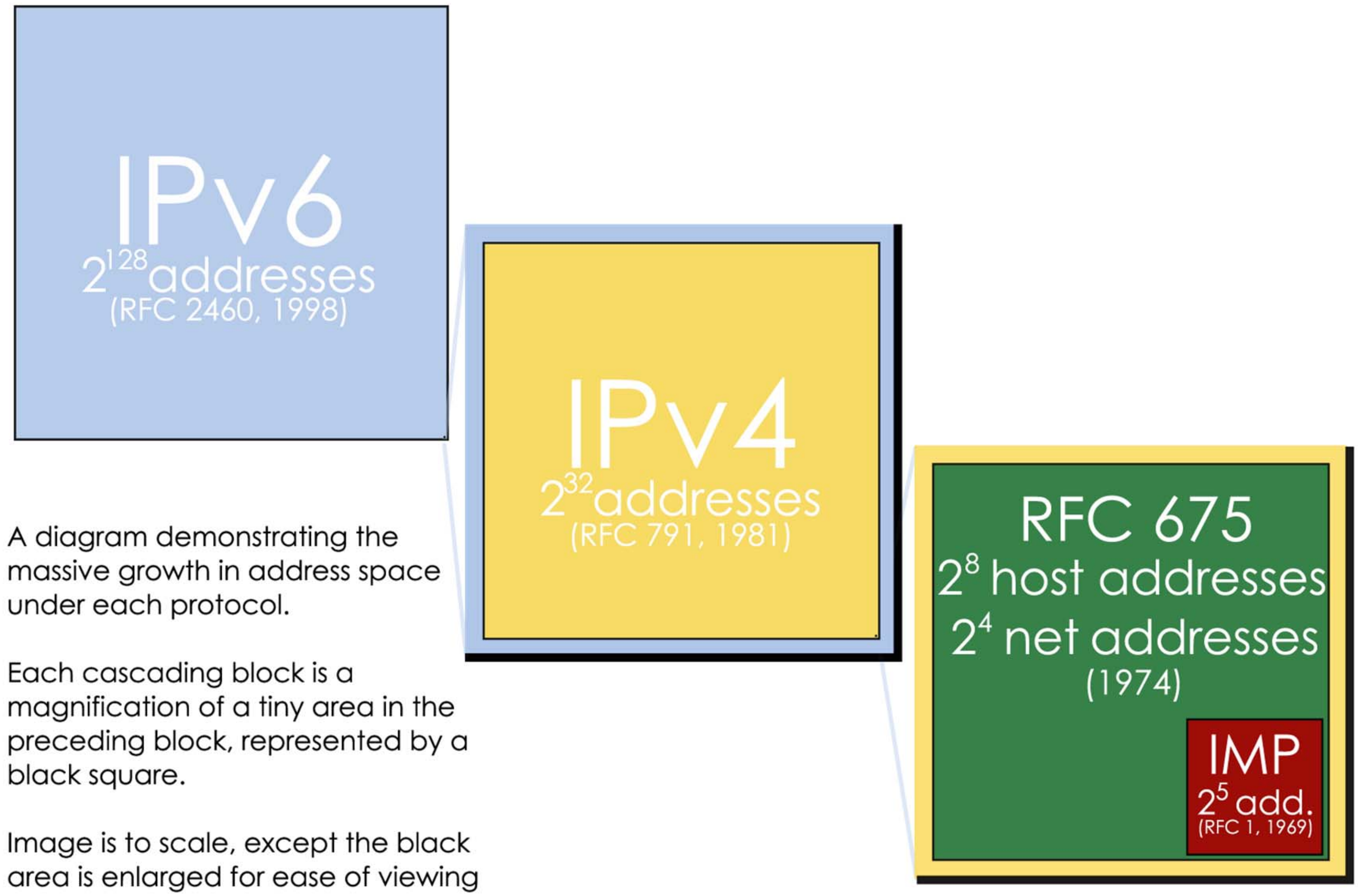
- IPv6 (RFC 2460) = the next generation Internet Protocol
  - Complete redesign of IP addressing
  - Hierarchical 128-bit address with decoupled host identifier
  - Stateless auto-configuration
  - Simple routing and address management

- 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

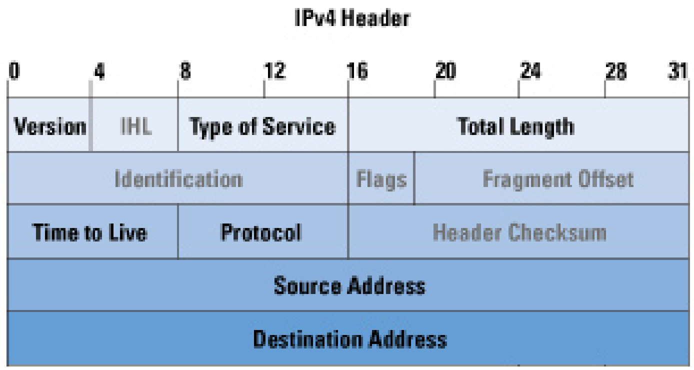
IPv4 vs. IPv6 Addressing

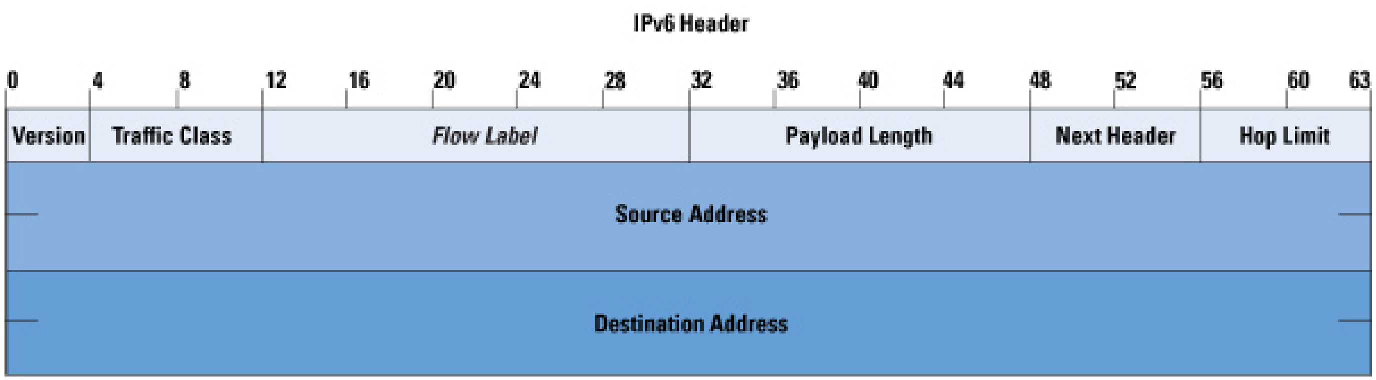


Address Space Comparison



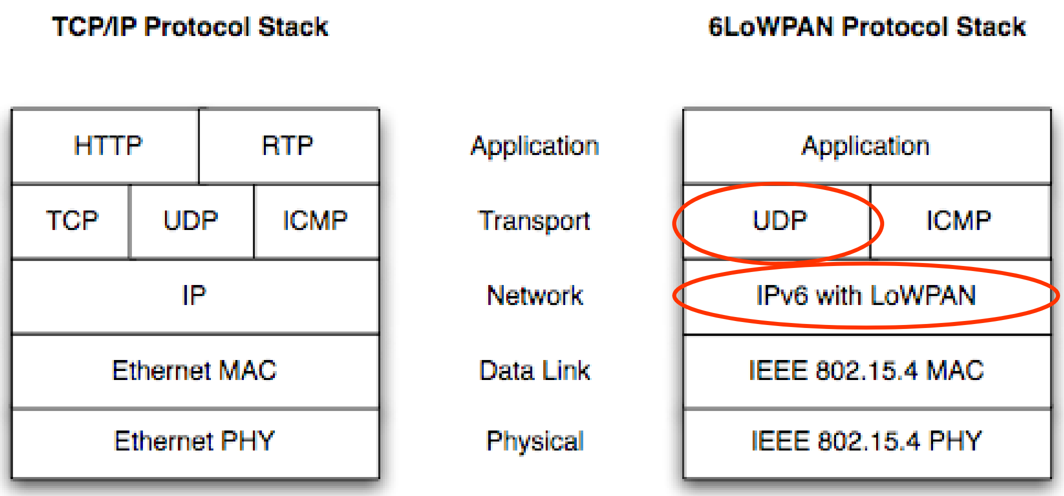
IPv4 vs. IPv6 Header





6LoWPAN Format

- 6LoWPAN is an adaptation header format
  - Enables the use of IPv6 over low-power wireless links
  - IPv6 header compression and UDP header compression



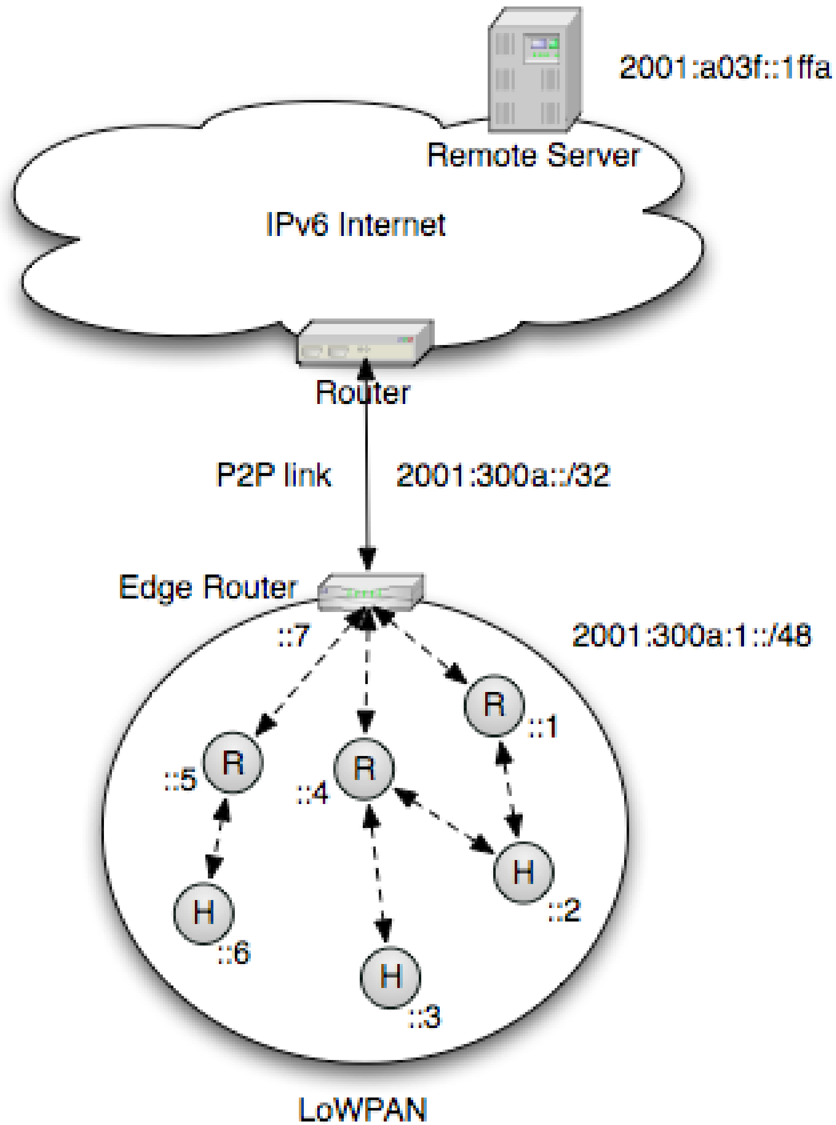
IPv6 Addressing

- 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

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

Addressing Example

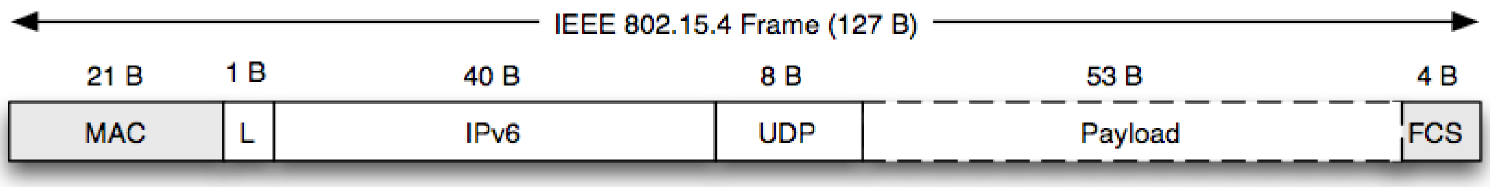


48 Bytes!

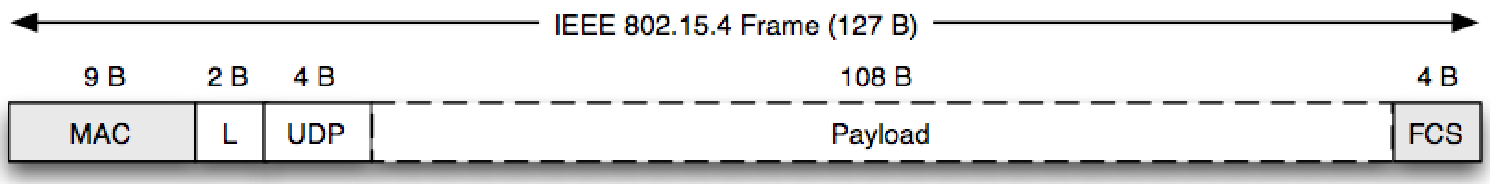
UDP/IPv6 Headers

```
                 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
                +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
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)

6LoWPAN Stateless Header Compression

From	To	Allocation
00 000000	00 111111	NALP – Not a LoWPAN frame (NALP)
01 000000		reserved for future use
01 000001		IPv6 – uncompressed IPv6 packets
01 000010		LOWPAN_HC1 – compressed IPv6, see Section 2.6.1
01 000011	01 001111	reserved for future use
01 010000		LOWPAN_BC0 – broadcast, see Section 2.8
01 010001	01 011111	reserved for future use
01 100000	01 111111	proposed for LOWPAN_IPHC, see Section 2.6.2
01 111111		ESC – Additional Dispatch byte follows (preempted by IPHC)
10 000000	10 111111	MESH – Mesh header, see Section 2.5
11 000000	11 000111	FRAG1 – Fragmentation Header (first), see Section 2.7
11 001000	11 011111	reserved for future use
11 100000	11 100111	FRAGN – Fragmentation Header (subsequent), see Section 2.7
11 101000	11 101011	proposed for fragment recovery [ID-thubert-sfr]
11 101100	11 111111	reserved for future use

6LoWPAN Stateless Header Compression

```
 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
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|0 1 0 0 0 0 1 0|SAE|DAE|C|NH |0|      Non-Compressed fields...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 \_ dispatch  _/ \_ HC1 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
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|0 1 0 0 0 0 1 0|SAE|DAE|C|NH |1|S|D|L|_________| N.-C. fields...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 \_ dispatch  _/ \_ HC1 header_/ \_ HC2 header_/
```

SAE or DAE value	Prefix	IID
00	sent in-line	sent in-line
01	sent in-line	elided and derived from L2 or mesh address
10	elided and assumed to be link-local (FE80::/64)	sent in-line
11	elided and assumed to be link-local (FE80::/64)	elided and derived from L2 or mesh address

00	Next header sent in-line
01	Next header = 17 (UDP)
10	Next header = 1 (ICMP)
11	Next header = 6 (TCP)

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

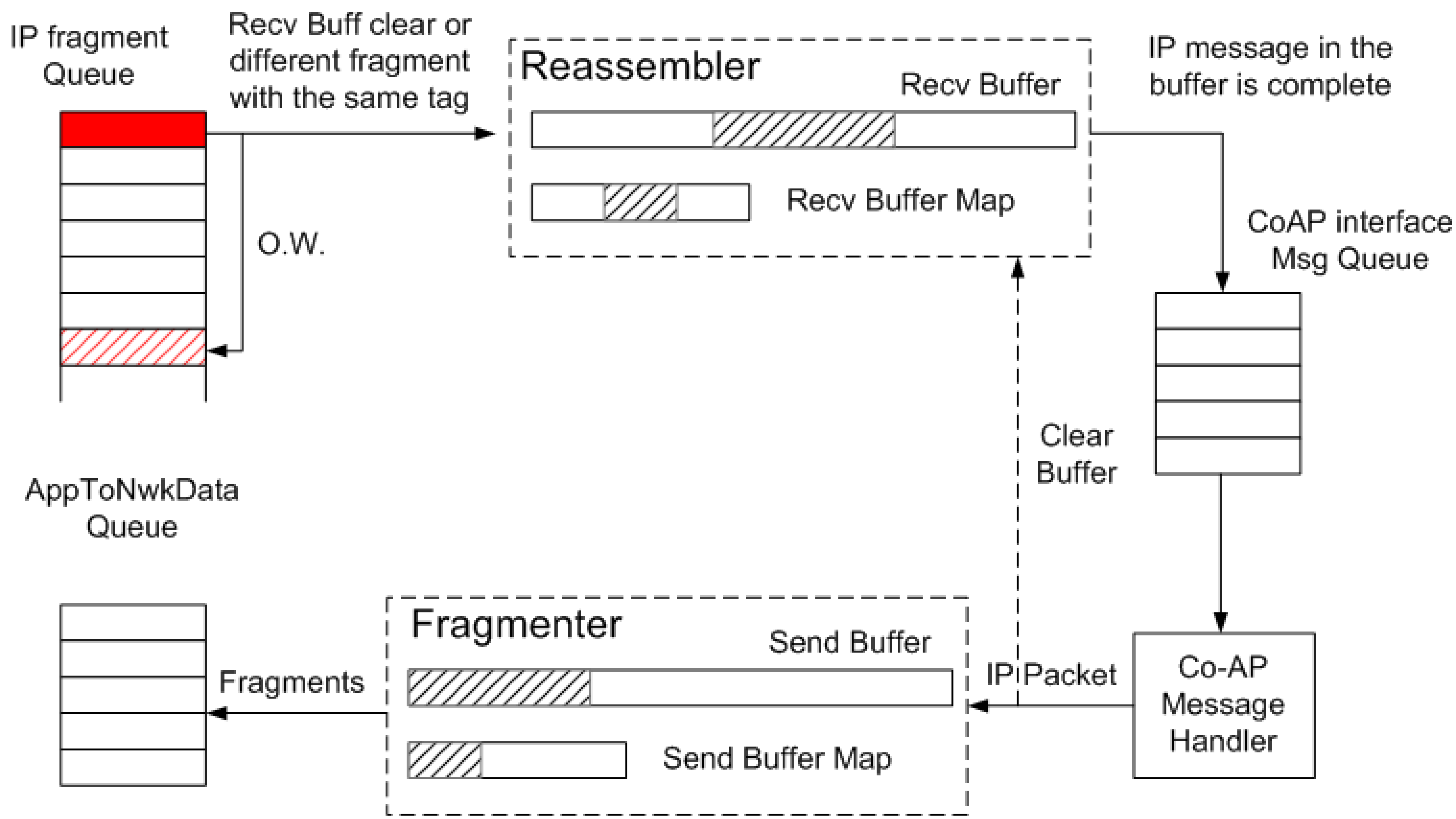
Initial 6LoWPAN fragment

```
                     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  _/
```

Non-initial 6LoWPAN fragment

```
                     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  _/
```

Fragmentation: An echo example



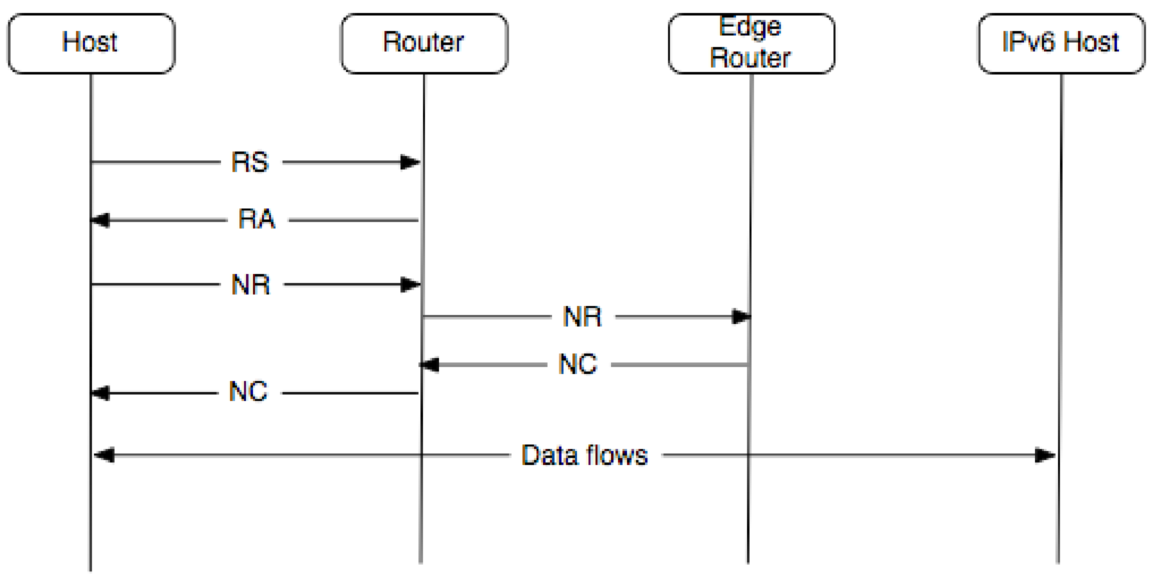
6LoWPAN Setup & Operation

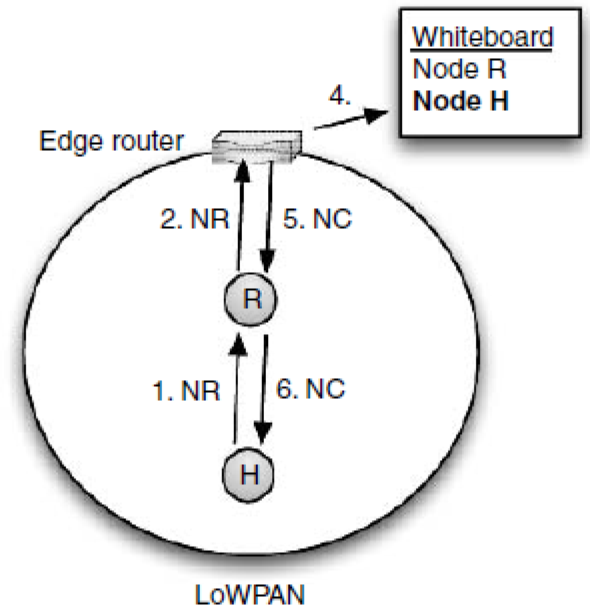
- Autoconfiguration is important in embedded networks
- In order for a 6LoWPAN network to start functioning:
  - Link-layer connectivity between nodes (commissioning)
  - Network layer address configuration, discovery of neighbors, registrations (bootstrapping)
  - Routing algorithm sets up paths (route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

Commissioning and Neighbor Discovery

- Link Layer Commissioning
  - In order for nodes to communicate with each other, they need to have compatible physical and link-layer settings.
- 6LoWPAN Neighbor Discovery provides:
  – An appropriate link and subnet model for low-power wireless addressing
  – Minimized node-initiated control traffic
  – Node Registration (NR) and Confirmation (NC)
  – Duplicate Address Detection (DAD) and recovery
  – Support for extended Edge Router infrastructures

Typical 6LoWPAN-ND Exchange

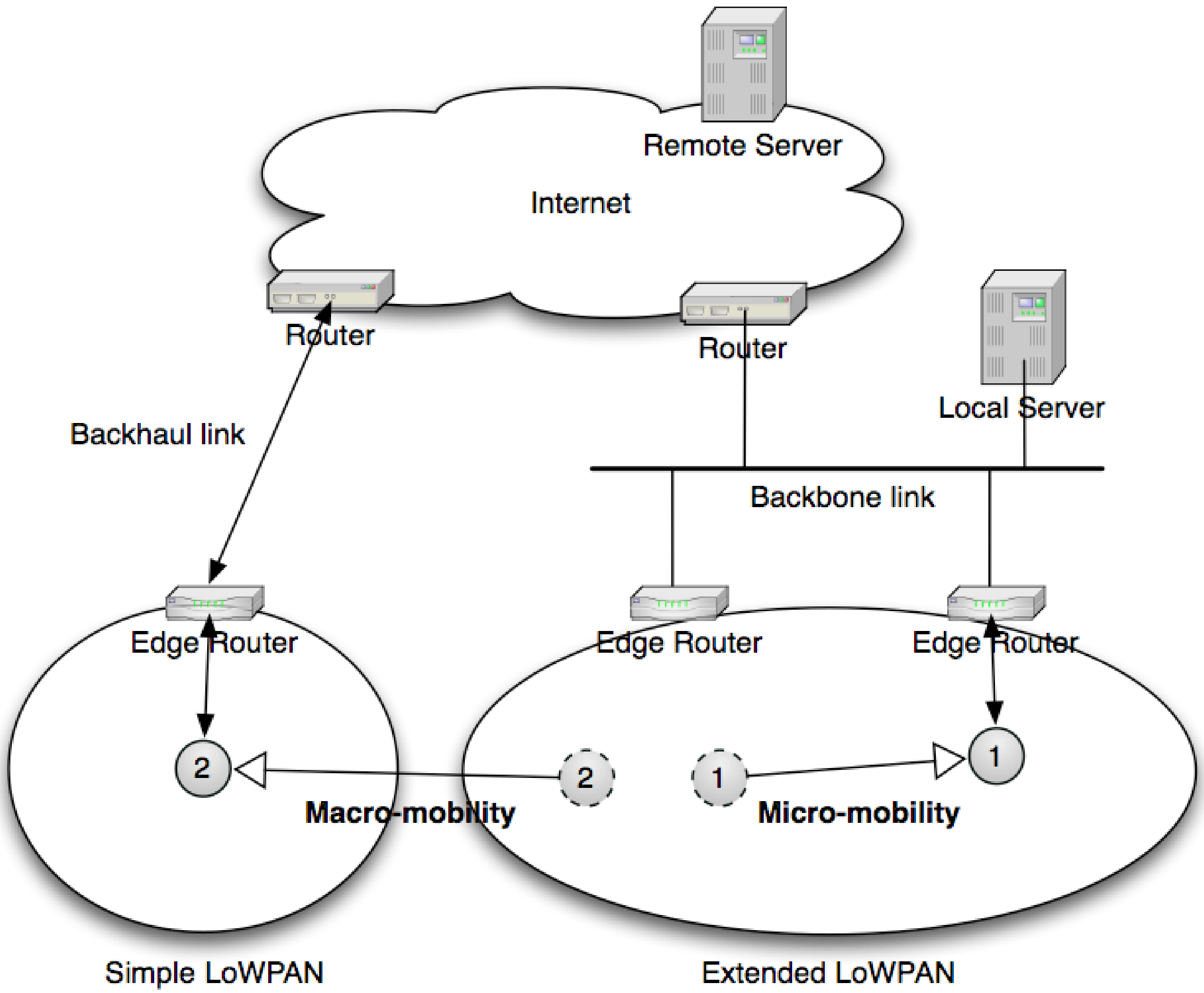




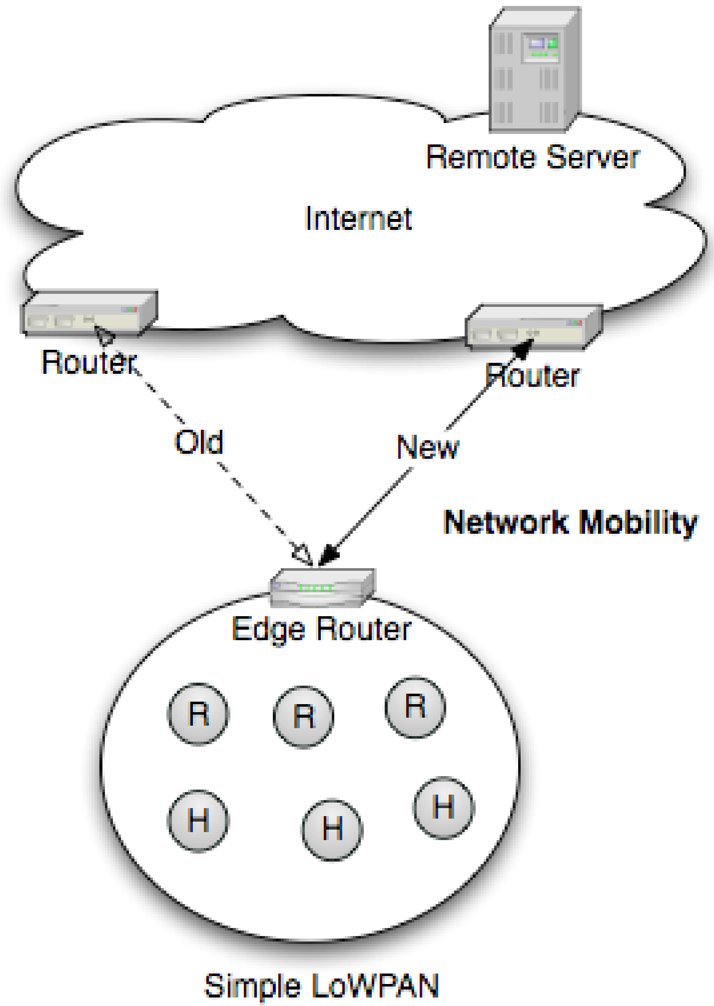
Mobility

- 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

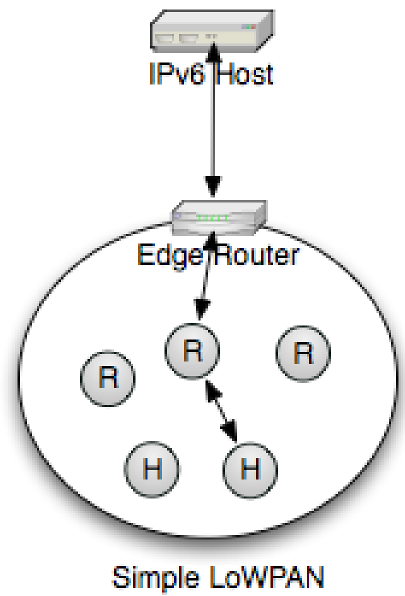


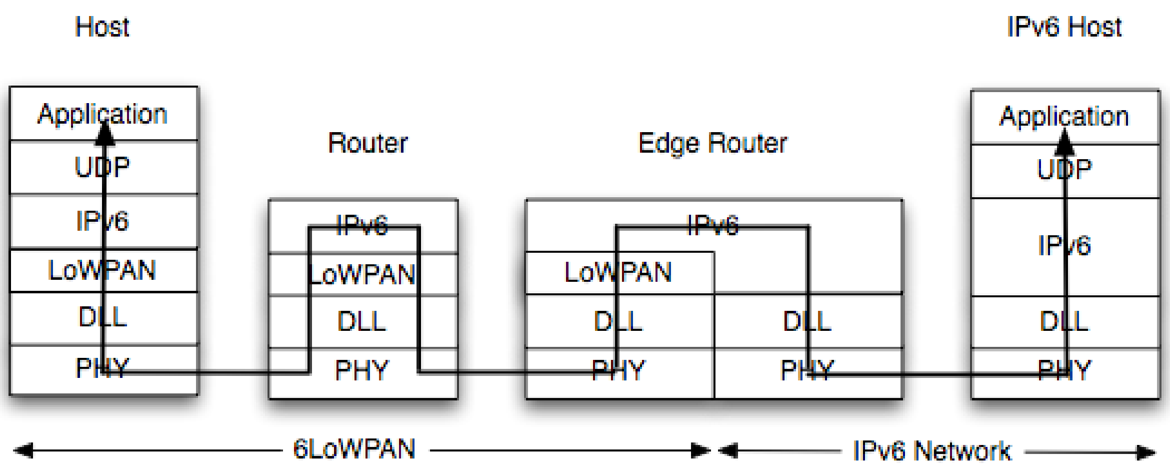
Dealing with Mobility

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

6LoWPAN Routing

- We consider IP routing
- Routing in a LoWPAN
  - Single-interface routing
  - Flat address space (exact-match)
  - Stub network (no transit routing)





Routing 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)
  - Developed specifically for embedded applications

Application Protocols

- 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

Application Protocols (Cont.)