Getting Started with IPv**6** in **Low-P**ower Wireless "Personal **A**rea" **N**etworks (6LoWPAN)

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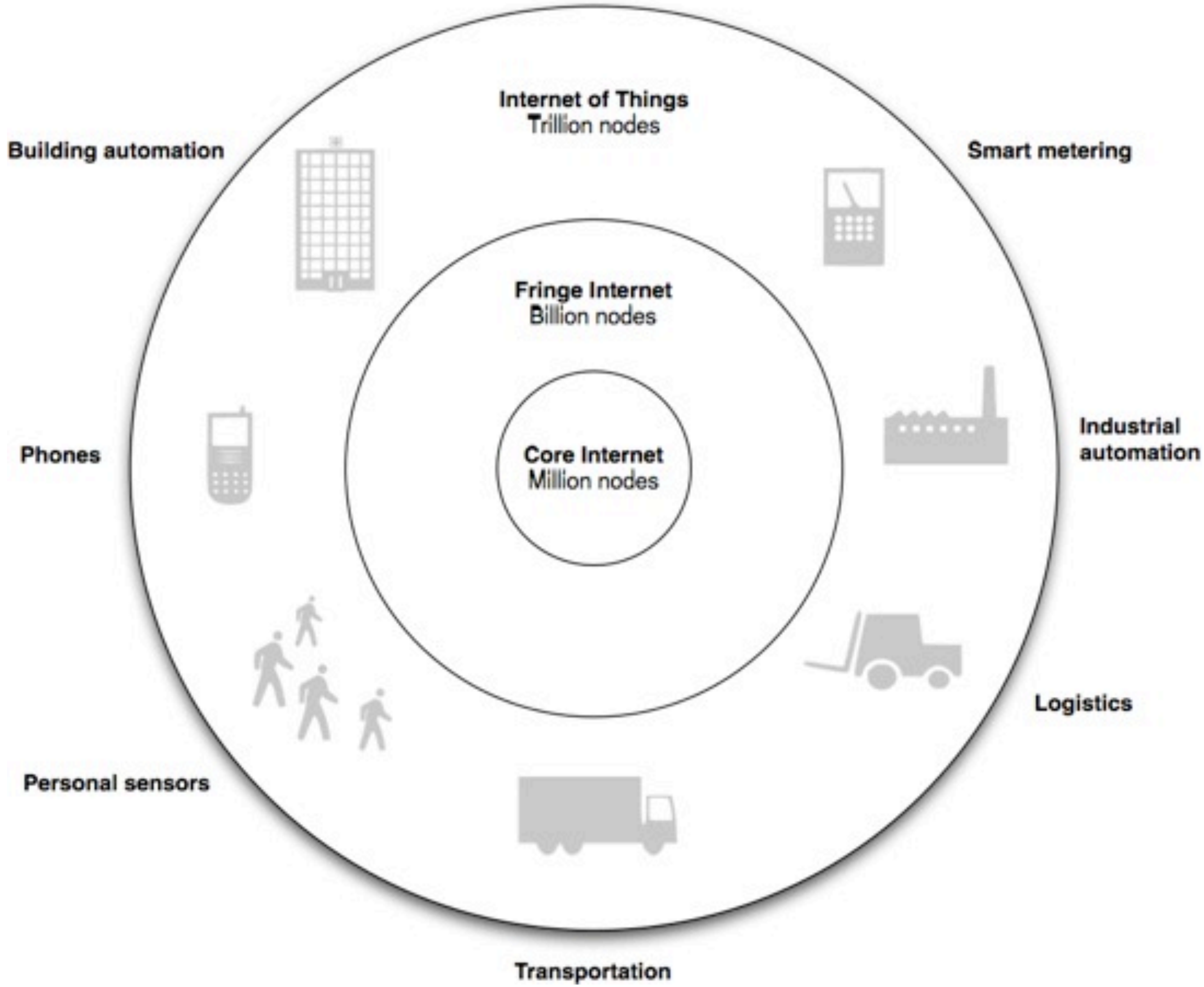
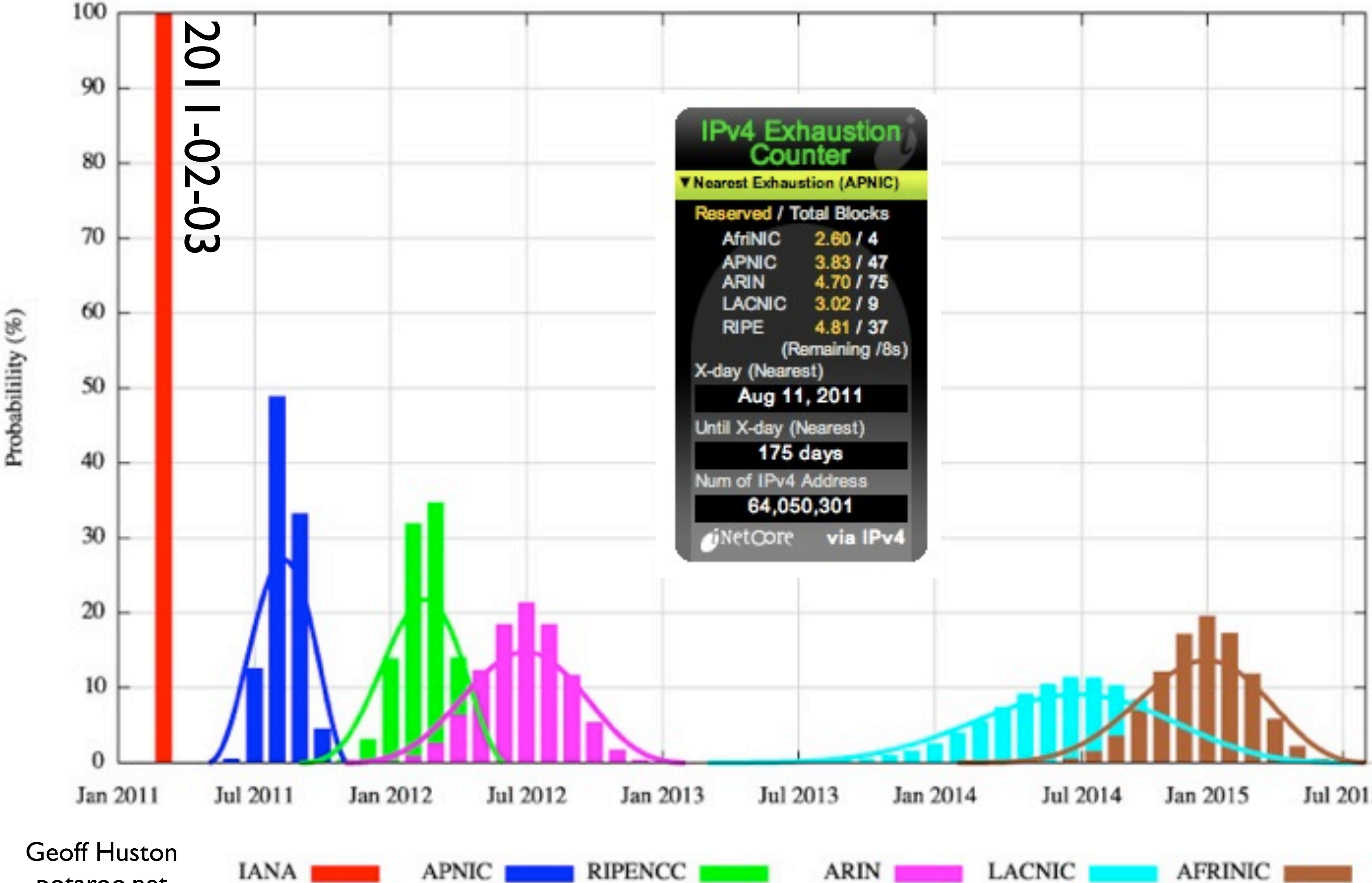
http://www.iab.org/about/workshops/smartobjects/tutorial.html



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

IPv4 Registry Exhaustion Dates



Geoff Huston
potaroo.net

IPv6 = $\underset{340282366920938463463374607431768211456}{3.4\times10^{38}}$ addresses

- There are only ~ 10^{25} grains of sand on the earth
- Let’s settle for a billion (**10^{9}**) objects on the net
- Danfoss (EU): 0.4×10^{9} thermostats so far
- Walmart (US): 0.1×10^{9} CFL light bulbs **per year**

Wires are too expensive

- Electrical wall socket + installation = $80
- Cat5 socket + installation = $150

- 1 billion nodes = GDP of Kuwait

Wireless?

Technology	Range	Speed	Power Use	Cost
WiFi	100 m	nn Mbit/s	high	$$$
Bluetooth	10–100 m	n Mbit/s	medium	$$
802.15.4	10–100 m	0.n Mbit/s	low	$

Constrained node/networks

Internet of Things	IoT
Low-Power/Lossy	LLN
IP Smart Objects	IPSO

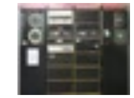
Constrained nodes

- **Node**: a few MHz, ~10 KiB RAM, ~100 KiB Flash/ROM
- Often battery operated — must sleep a lot
  (mW • (1.0–(99.9 %)) = µW!)

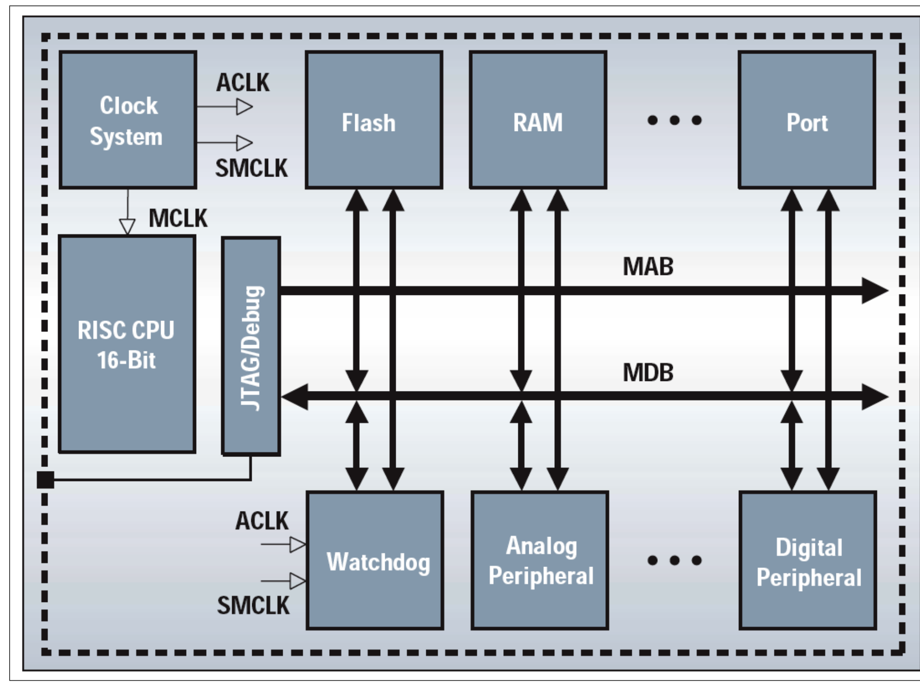
- Moore’s law will fix it?
- Moore’s law will be used mostly
  - to make things cheaper,
  - more energy efficient!

http://www.flickr.com/photos/blahflowers/3878202215/sizes/l/

Example: MSP430



- Texas Instruments mixed-signal uC
- 16-bit RISC
- ROM: 1-60 KiB
- RAM: Up to 10 KiB
- Analogue
  - 12 bit ADC & DAC
  - LCD driver
- Digital
  - USART x 2
  - DMA controller
  - Timers

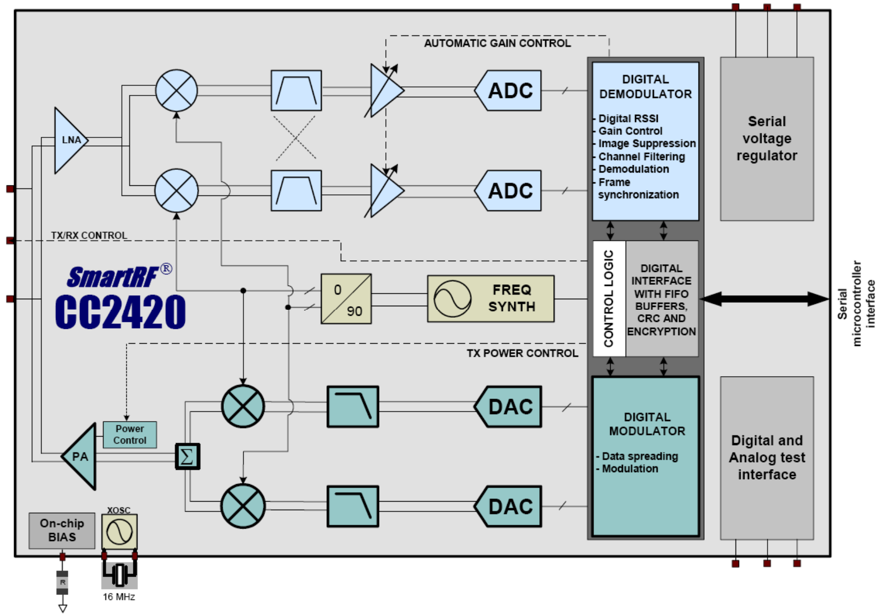


Example: CC2420

cf. CC2431: Add an 8051-style processor, 8 KB RAM, 128 KB Flash

- IEEE 802.15.4 compliant radio
- 2.4 GHz band using DSSS at 250 kbps
- Integrated voltage regulator
- Integrated digital baseband and MAC functions
  - Clear channel assessment
  - Energy detection (RSSI)
  - Synchronization
  - Framing
  - Encryption/authentication
  - Retransmission (CSMA)

Sleep	Idle	Tx	Rx
20 uA	426 uA	8.5 – 17.4 mA	18.8 mA



Power Consumption

A simple approximation for power consumption:

$$P_{avg} = \frac{1}{T_F}\left\{P_{Rx}T_{wk-up} + P_{Rx}(N_{Tx}T_{Tx-up} + N_{Rx}T_{Rx-up}) + P_{Tx}T_{Tx} + P_{Rx}T_{Rx} + P_{idle}T_{idle} + P_{sleep}T_{sleep}\right\}$$

T_{wk-up} = Time that takes to go from sleep state to awake state
T_{Tx-up} = Transmitter setup time, i.e. time it takes for the transmitter to be ready
T_{Tx} = Time in the *Tx* state
T_{Rx-up} = Receiver setup time, i.e. time it takes for the receiver to be ready
T_{Rx} = Time in the *Rx* state
T_{idle} = Time in the idle state
T_{sleep} = Time in the sleep state
N_{Tx} = Average number of times per frame that the transmitter is used
N_{Rx} = Average number of times per frame that the receiver is used
T_F = Duration of the time frame
P_{Tx} = Power used in the *Tx* state
P_{Rx} = Power used in the *Rx* state
P_{idle} = Power used in the idle state
P_{sleep} = Power used in the sleep state
P_{avg} = Average power used by the transceiver

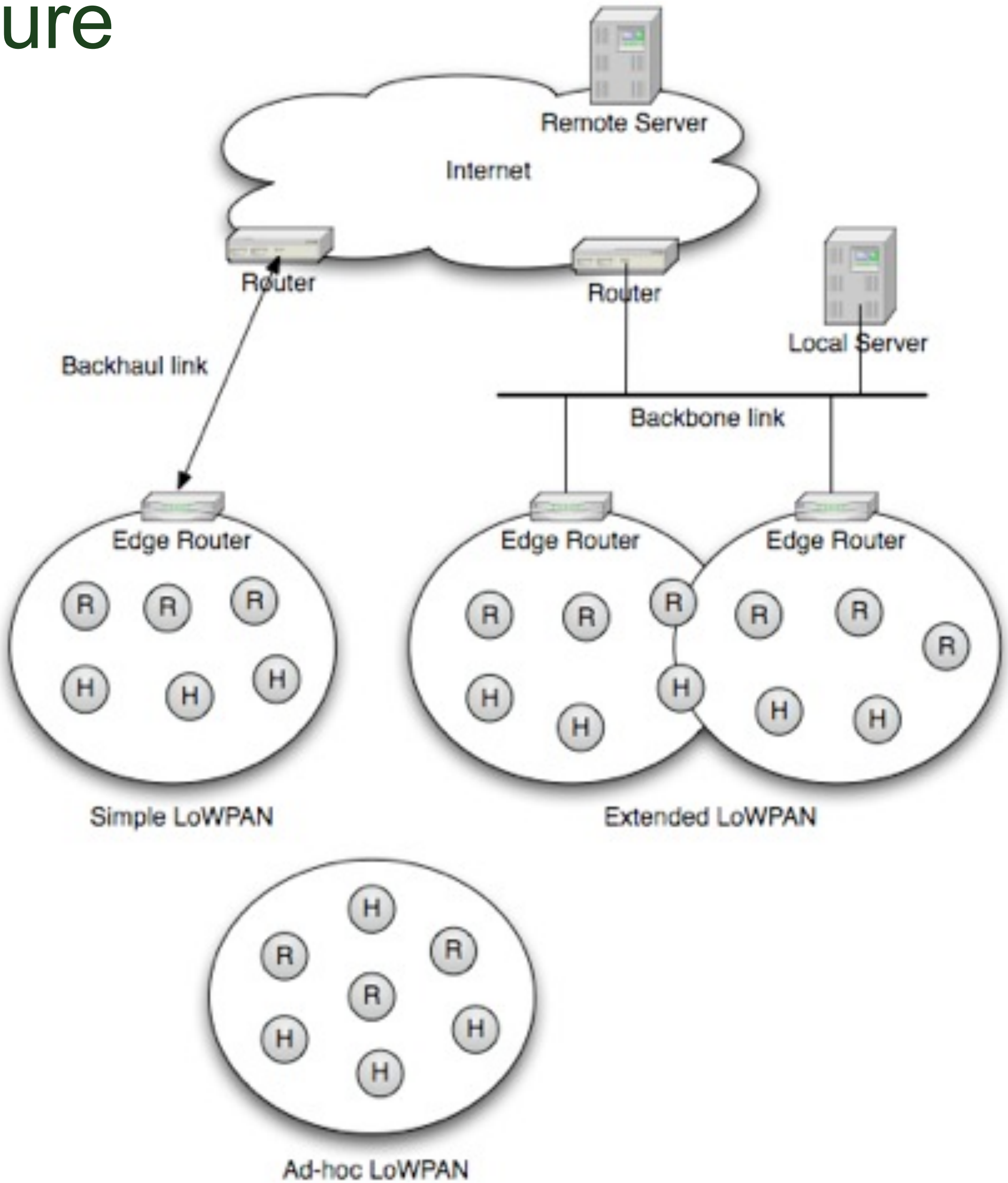
Constrained networks

- **Node**: ... must sleep a lot (µW!)
  - vs. “always on”
- **Network**: ~100 kbit/s, high loss,
  high link variability
- May be used in an unstable radio environment
- Physical layer packet size may be limited
  (~100 bytes)
- “LLN low power, lossy network”

Constrained network example: IEEE 802.15.4

- popular low-power (~ 1 mW) radio
- 0.9 and 2.4 GHz bands
  - 868 MHz: Europe (1 % duty cycle, 20 kbit/s)
  - 900 MHz: US (40 kbit/s)
  - 2.4 GHz: World (256 kbit/s)
- up to 127-byte packets

Architecture



Constrained node/networks in the IETF

- IETF WGs to date:

6LoWPAN	ROLL	CoRE
INT area (Internet) L2/L3 interface	RTG area (Routing) L3 routing	APP area (Applications) L7 application
(now)	JP Vasseur	Zach Shelby

Adam Dunkels

- New: **LWIG** (INT area, Light-Weight Implementation Guidance)

6LoWPAN: IPv6 over Low-Power Area Networks (IEEE 802.15.4)

- IETF WG chartered in 2005 to define IPv6 over IEEE **802.15.4**
- Two initial deliverables approved 2007-05-01
  - RFC 4919: Problem statement (“Goals and Assumptions”)
  - **RFC 4944**: Format specification (“IPv6 over 802.15.4”)

RFC 4944: make 802.15.4 look like an IPv6 link

2007

- Basic **Encapsulation**
  - Efficient representation of packets < ~100 bytes
  - First approach to **stateless** Header Compression
- **Fragmentation** (map 1280 byte MTU to < 128 bytes)
  - Datagram tag/Datagram offset
- Mesh forwarding
  - Identify Originator/Final Destination
- Minimal use of complex MAC layer concepts
  - cf. RFC 3819 “Advice for Internet Subnetwork Designers”

The dispatch byte: replacement Ethertype

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

Space later taken by 6LoWPAN-HC

LoWPAN UDP/IPv6 Headers

6 Bytes!

LoWPAN Dispatch byte provides multiplexing

IPv6

UDP

Compressed port numbers

```
 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

using draft-ietf-6lowpan-hc format (see later)

Fragmentation

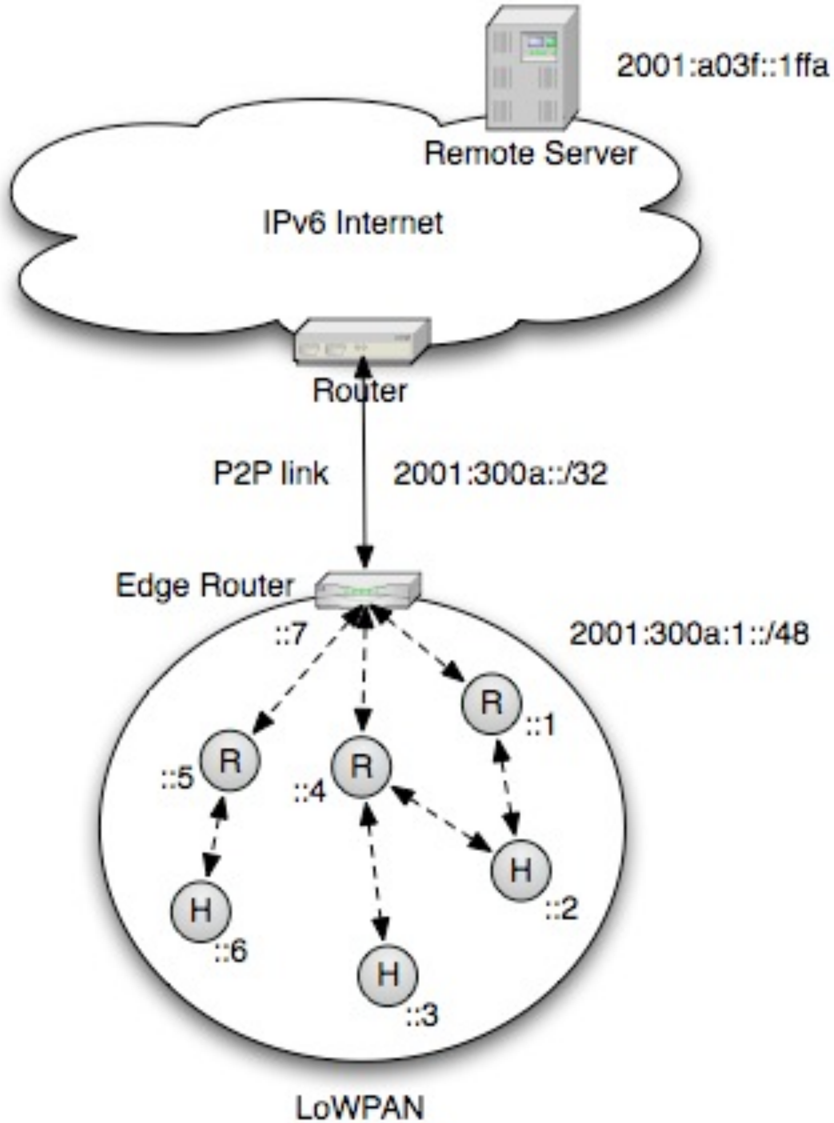
LoWPAN Dispatch byte provides multiplexing

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

6LoWPAN-ND

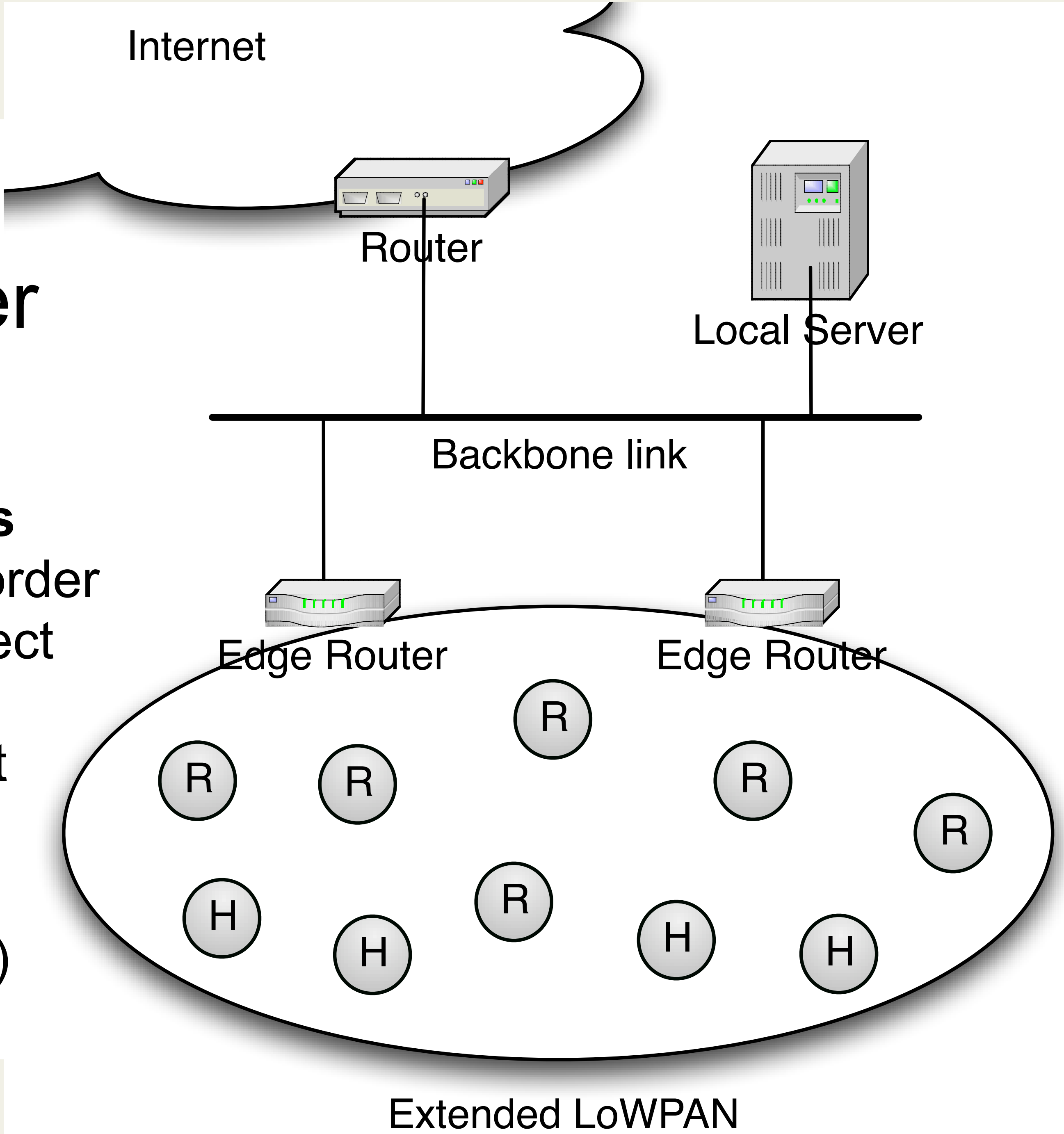
- Classic IPv6: link ≡ multicast domain
  - could be realized by **mesh-under** (L2 routing) protocol
  - can be substituted by less multicast-reliant ND
- RFC 5889: **ad-hoc link model**
  - Alternative: confine link to radio domain
  - multicast is local only
  - need **route-over** (L3 routing) protocol
    to build larger 6lowpan
- Both mesh-under and route-over
  covered by single architecture

Addressing Example



Route-Over

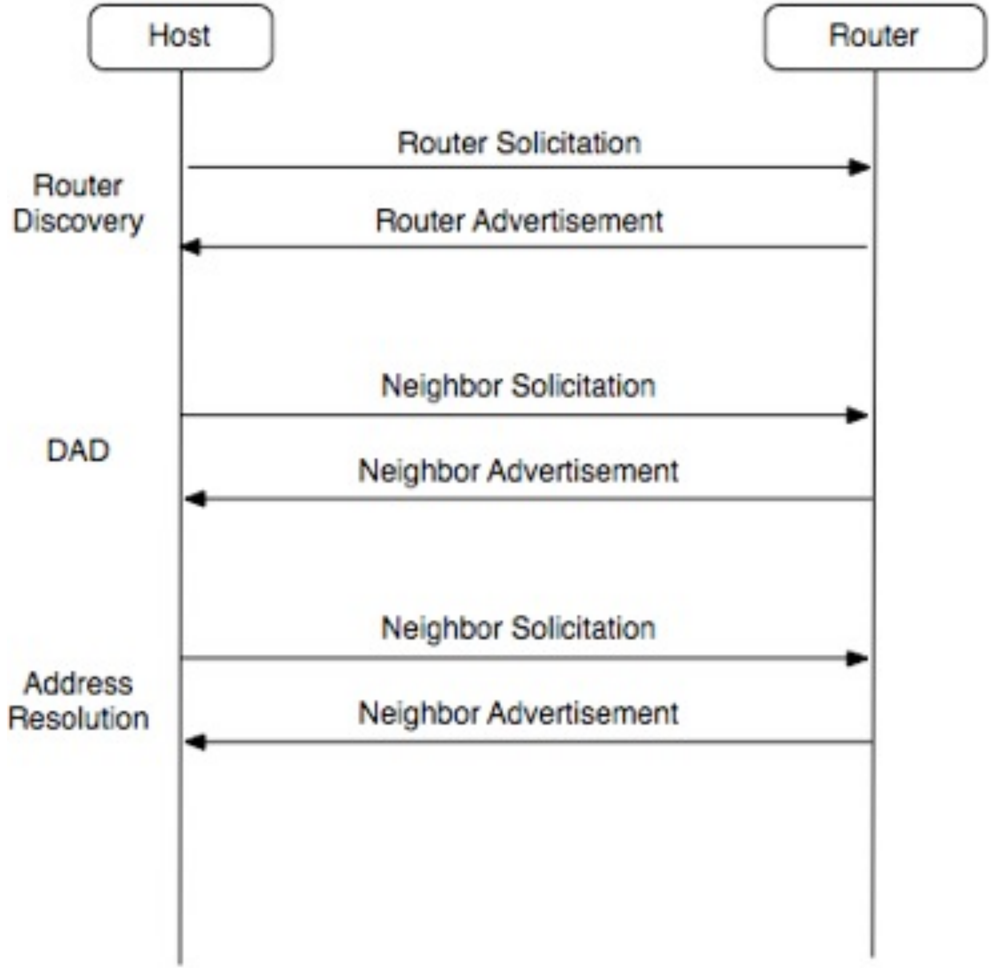
- One or more **Edge Routers** (6LoWPAN border routers) connect 6LoWPAN to global Internet
- 6LoWPAN comprises routers (6LRs) and hosts



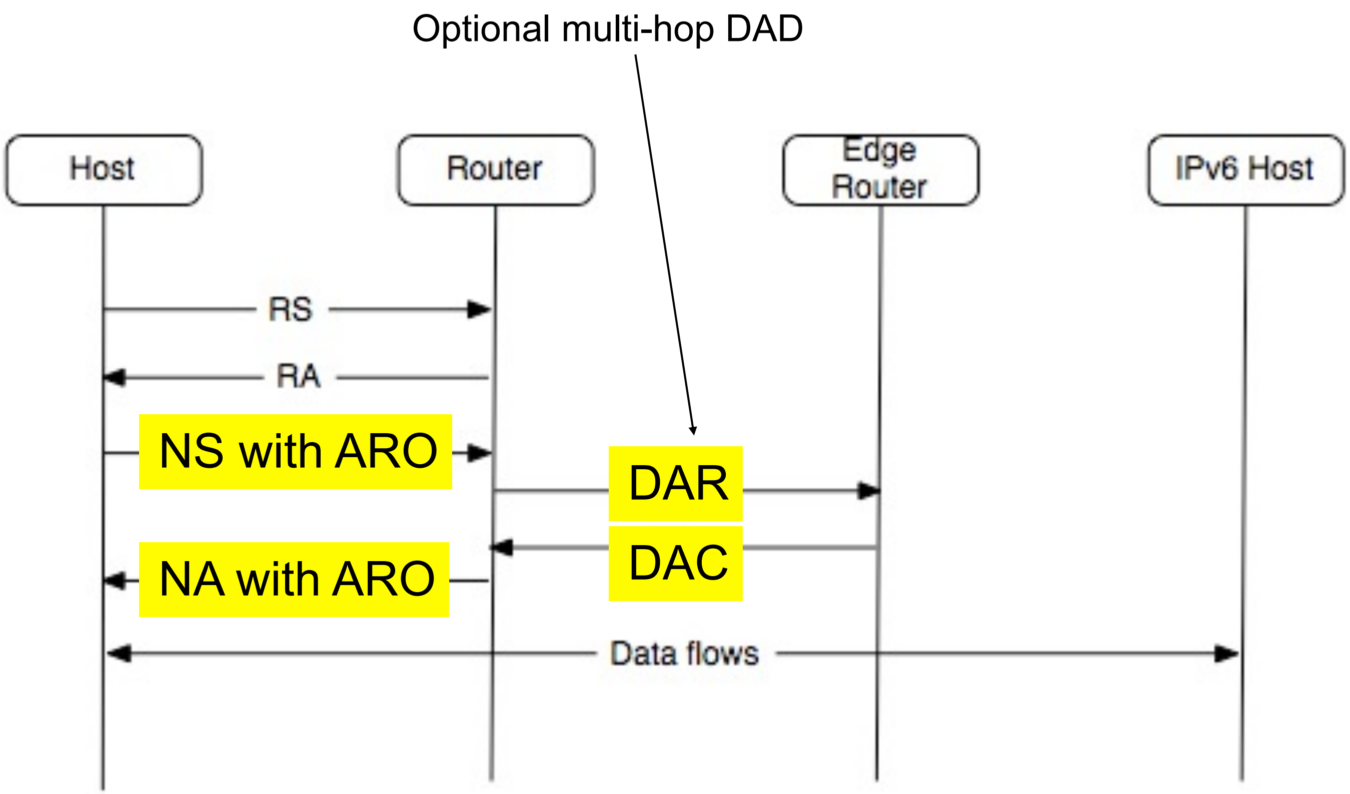
Host-Router Interface

- Hosts only talk to routers
- Routers *may* redirect to hosts in mesh-under
  - no direct host-host communication in route-over (wouldn't be awake anyway...)

Classic IPv6 Neighbor Discovery (4861)



Typical 6LoWPAN-ND Exchange



6LoWPAN-ND elements beyond 4861

- **ARO** (address registration option):
  - hosts register their addresses to routers (6LRs): NS/NR
  - 6LRs can check the address with edge router (6LBR): new ICMP messages **DAR/DAC**
  - replaces NS/NR use for address resolution (off-link model), but keeps NS/NR intact for NUD (neighbor unreachability detection)

ARO Option

Reserved

```
 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      |  Length = 2   |    Status     |_______________|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|_______________________________|     Registration Lifetime     |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                            EUI-64                             +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

```
Registration Lifetime:  16-bit unsigned integer.  Time in units of 60 s
```

6LoWPAN-ND elements beyond 4861

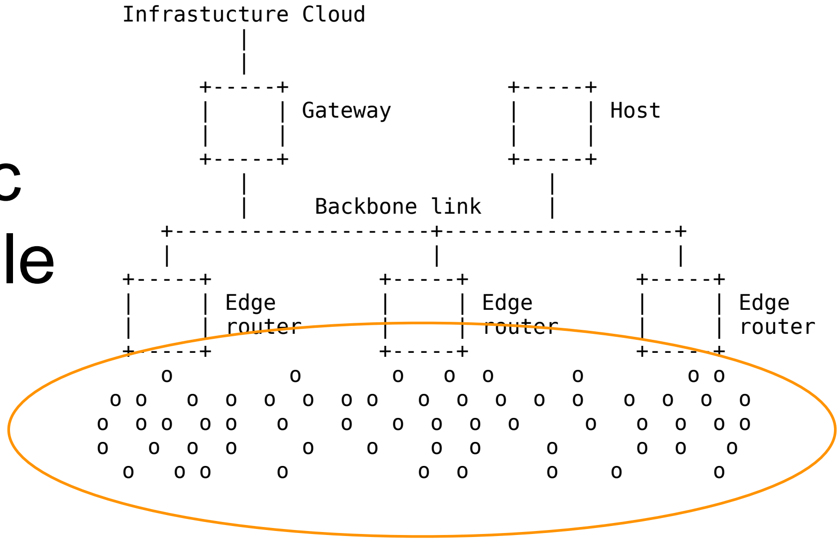
- **ABRO** (authoritative border router option)
  - distribute information about available 6LBRs (edge routers)
- **6CO** (6LoWPAN Context Option)
  - distribute **header compression** context in entire LoWPAN

Header Compression

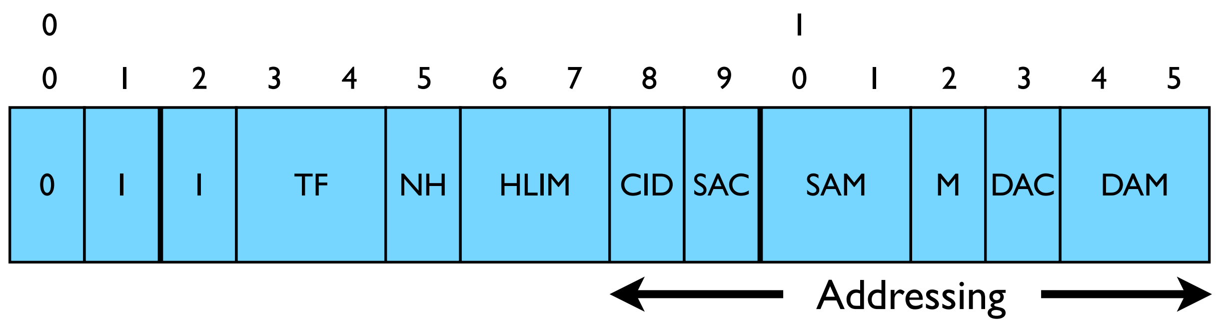
- Organized Layer Violation
  - compress L3+ headers on L3-L2 interface
- Traditional header compression (ROHC, RFC 3095 etc.) is **flow-based stateful**
  - exploit redundancies **between** packets
- RFC 4944 header compression is **stateless**
  - exploit **intra-packet** redundancies only
  - Can't compress global prefix

6LoWPAN-HC: Header Compression

- Is there a middle ground?
- draft-bormann-6lowpan-cbhc (2008-07): introduced a single **area context state** for an entire 6LoWPAN



IPv6 Header Compression

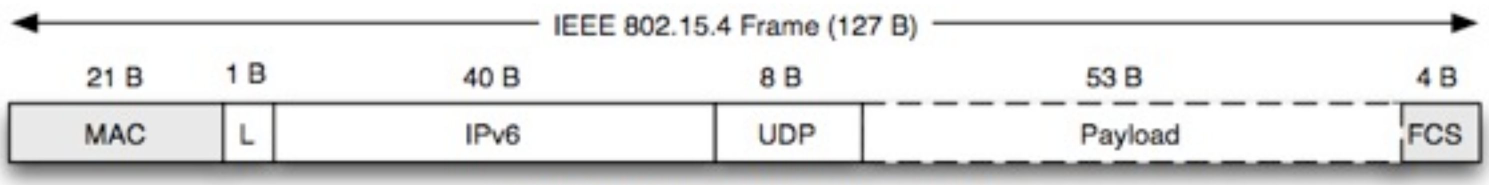


TF	2 bits	Traffic Class and Flow Label
NH	1 bit	Next Header
HLIM	2 bits	Hop Limit
CID	1 bit	Context Identifier Extension
SAC	1 bit	Source Address Context
SAM	2 bits	Source Address Mode
M	1 bit	Multicast Address Compression
DAC	1 bit	Destination Address Context
DAM	2 bits	Destination Address Mode

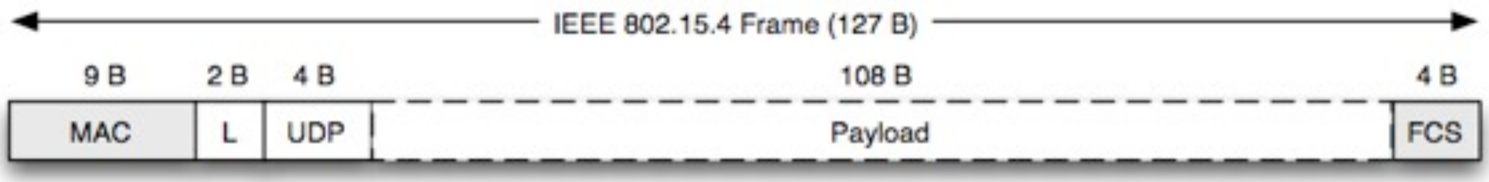
[Hui]

6LoWPAN Headers

- Orthogonal header format for efficiency
- Stateless header compression

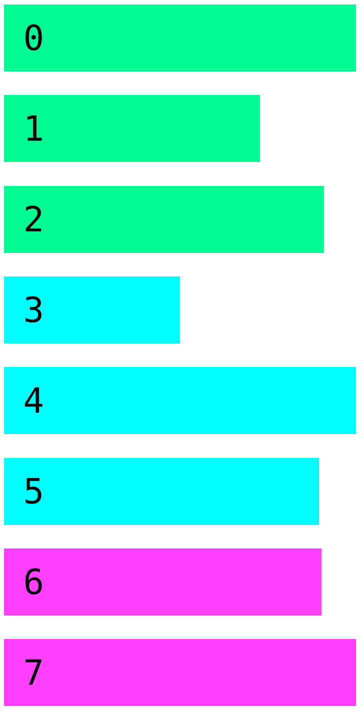


Full UDP/IPv6 (64-bit addressing)



Minimal UDP/6LoWPAN (16-bit addressing)

Area context state



- up to 16 contexts, each with
  - a prefix (up to 128 bits), given by value and length
- Used in **6LoWPAN-HC** compression methods:
  - carry the variable bits in packet
  - infer variable bits from L2 addresses
  - special method for multicast addresses
- **6LoWPAN-ND** Context Option (6CO)
  - distribute context throughout 6LoWPAN
  - defined as part of 6LoWPAN-ND

LOWPAN-NHC: Next Header

Compression beyond IP header:

- UDP: Can compress ports (from 61616 to 61631)
- Extension headers:
  - IPv6 Hop-by-Hop Options Header
  - IPv6 Routing Header
  - IPv6 Fragment Header
  - IPv6 Destination Options Header
  - IPv6 Mobility Header [RFC3775]
  - IPv6 Header (for compressing Tunneling)

New proposal: 6LoWPAN-GHC

- Generic compression of remaining headers and header-like payloads: ICMPv6, ND, RPL; DHCP; ...
- draft-bormann-6lowpan-ghc: simple LZ77 based on **bytecode**
  - **single-page** specification: simple
  - **stateless** (but can use 6LoWPAN-HC context)
- provides modest compression factors between 1.65 and 1.85 on realistic examples

code byte	Action	Argument
0kkkkkkk	Append k = 0b0kkkkkkk bytes of data in the bytecode argument (k < 96)	The k bytes of data
0110iiii	Append all bytes (possibly filling an incomplete byte with zero bits) from Context i	
0111iiii	Append 8 bytes from Context i; i.e., the context value truncated/extended to 8 bytes, and then append 0000 00FF FE00 (i.e., 14 bytes total)	
1000nnnn	Append 0b0000nnnn+2 bytes of zeroes	
1001nnnn	reserved	
101nssss	sa += 0b0ssss000, na += 0b0000n000	
11nnnkkk	n = na+0b00000nnn+2; s = 0b00000kkk+sa+n; append n bytes from previously output bytes, starting s bytes to the left of the current output pointer; set sa = 0, na = 0	

Example: ND Neighbor Solicitation

```
Payload:
 87 00 a7 68 00 00 00 00 fe 80 00 00 00 00 00 00
 02 1c da ff fe 00 30 23 01 01 3b d3 00 00 00 00
 1f 02 00 00 00 00 00 06 00 1c da ff fe 00 20 24
Pseudoheader:
 20 02 0d b8 00 00 00 00 00 00 00 ff fe 00 3b d3
 fe 80 00 00 00 00 00 00 02 1c da ff fe 00 30 23
 00 00 00 30 00 00 00 3a
copy: 04 87 00 a7 68
4 nulls: 82
ref(32): fe 80 00 00 00 00 00 00 02 1c da ff fe 00 30 23
 -> ref 101nssss 1 2/11nnnkkk 6 0: b2 f0
copy: 04 01 01 3b d3
4 nulls: 82
copy: 02 1f 02
5 nulls: 83
copy: 02 06 00
ref(24): 1c da ff fe 00 -> ref 101nssss 0 2/11nnnkkk 3 3: a2 db
copy: 02 20 24
Compressed:
 04 87 00 a7 68 82 b2 f0 04 01 01 3b d3 82 02 1f
 02 83 02 06 00 a2 db 02 20 24
Was 48 bytes; compressed to 26 bytes, compression factor 1.85
```

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

6LoWPAN status

- 6LoWPAN widely accepted as the way to run IP on 802.15.4
  - RFC 4944 published September 2007
  - Adoption in TinyOS, Contiki; Standards: ISA100, ZigBee SE 2.0, ...
- Recent interoperability events for both 6LoWPAN-ND/ 6LoWPAN-HC: **10+ implementations each**
- 6LoWPAN-HC (HC-15) in IESG (last step before RFC)
  - remaining issue: checksum omission (vs. draft-ietf-6man-udpzero-02)
- 6LoWPAN-ND (ND-15) went through second WG last call
  - remaining technical discussion next week before submitting to IESG

6LoWPAN =

RFC4944
– HC1/HC2
+ 6LoWPAN-HC
+ 6LoWPAN-ND