Wireless Embedded Systems and Networking

Foundations of IP-based Ubiquitous Sensor Networks

6LoWPAN

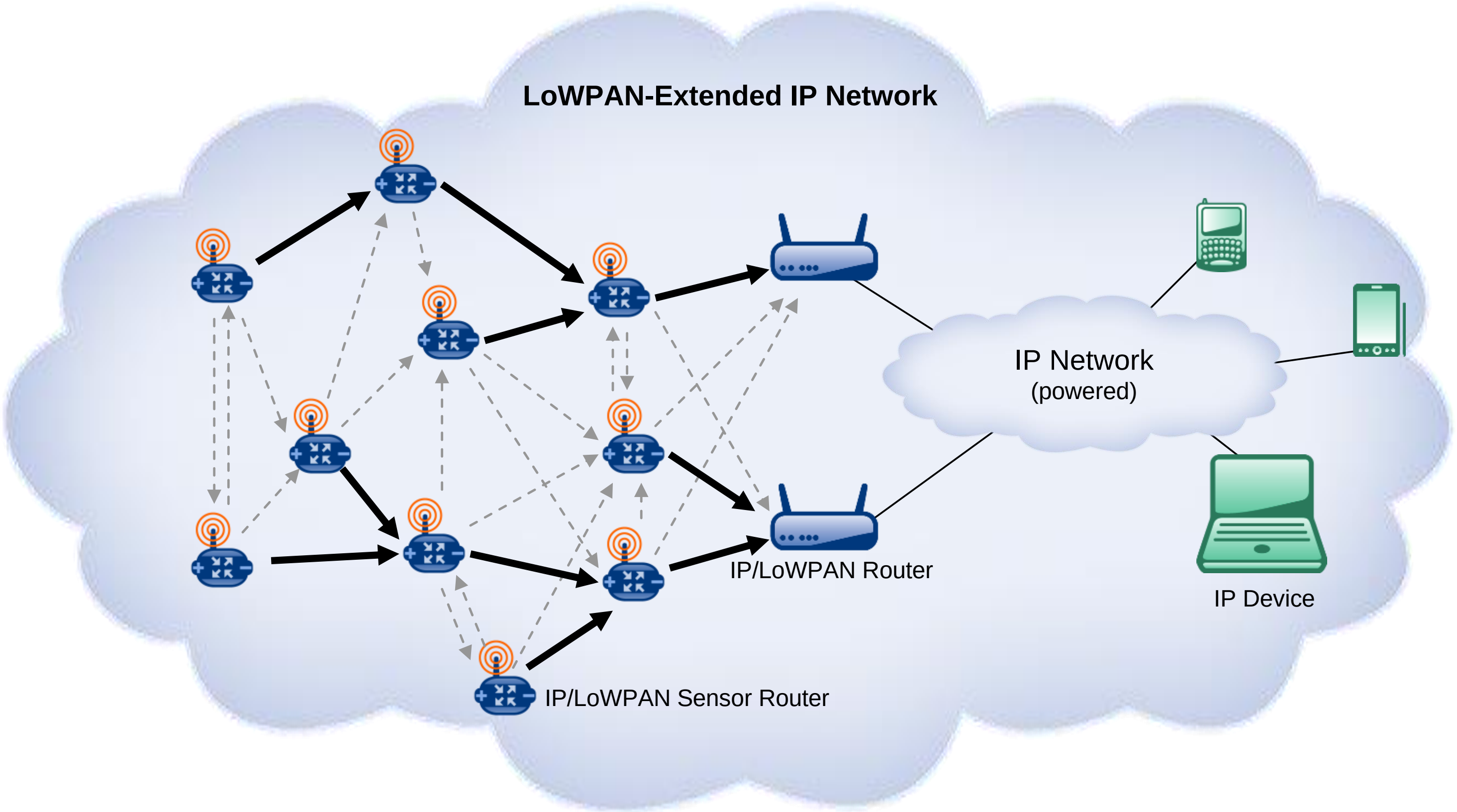
David E. Culler

University of California, Berkeley

Arch Rock Corp.

July 11, 2007

2007 - The IP/USN Arrives



ArchRock

IEEE 802.15.4 – The New IP Link

- http://www.ietf.org/internet-drafts/draft-ietf-6lowpan-format-13.txt
  - Please refer to the internet draft / RFCs for definitive reference
- 1% of 802.11 power, easier to embed, as easy to use.

THE Question

If Wireless Sensor Networks represent a future of "billions of information devices embedded in the physical world,"

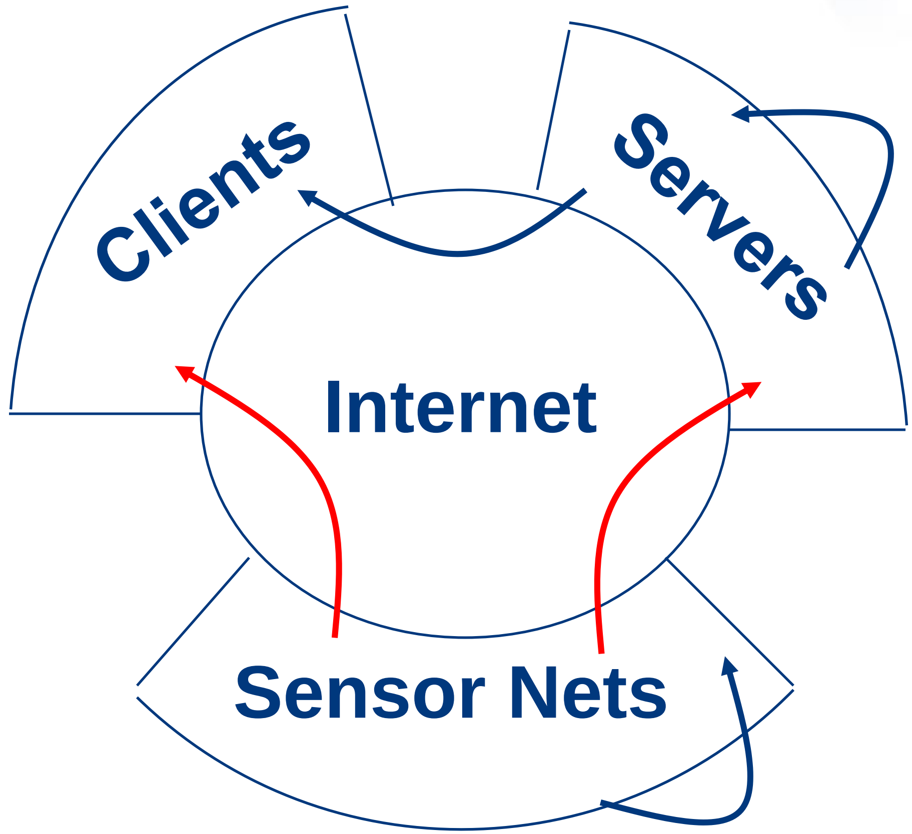
why don't they run ***<u>THE</u>*** standard internetworking protocol?

The Answer

They should

- Substantially advances the state-of-the-art in both domains.
- Implementing IP requires tackling the general case, not just a specific operational slice
  - Interoperability with all other potential IP network links
  - Potential to name and route to any IP-enabled device within security domain
  - Robust operation despite external factors
    - Coexistence, interference, errant devices, ...
- While meeting the critical embedded wireless requirements
  - High reliability and adaptability
  - Long lifetime on limited energy
  - Manageability of many devices
  - Within highly constrained resources

Wireless Sensor Networks
The Next Tier



How will SensorNets and IP play together?

XML / RPC / REST / SOAP / OSGI

HTTP / FTP / SNMP

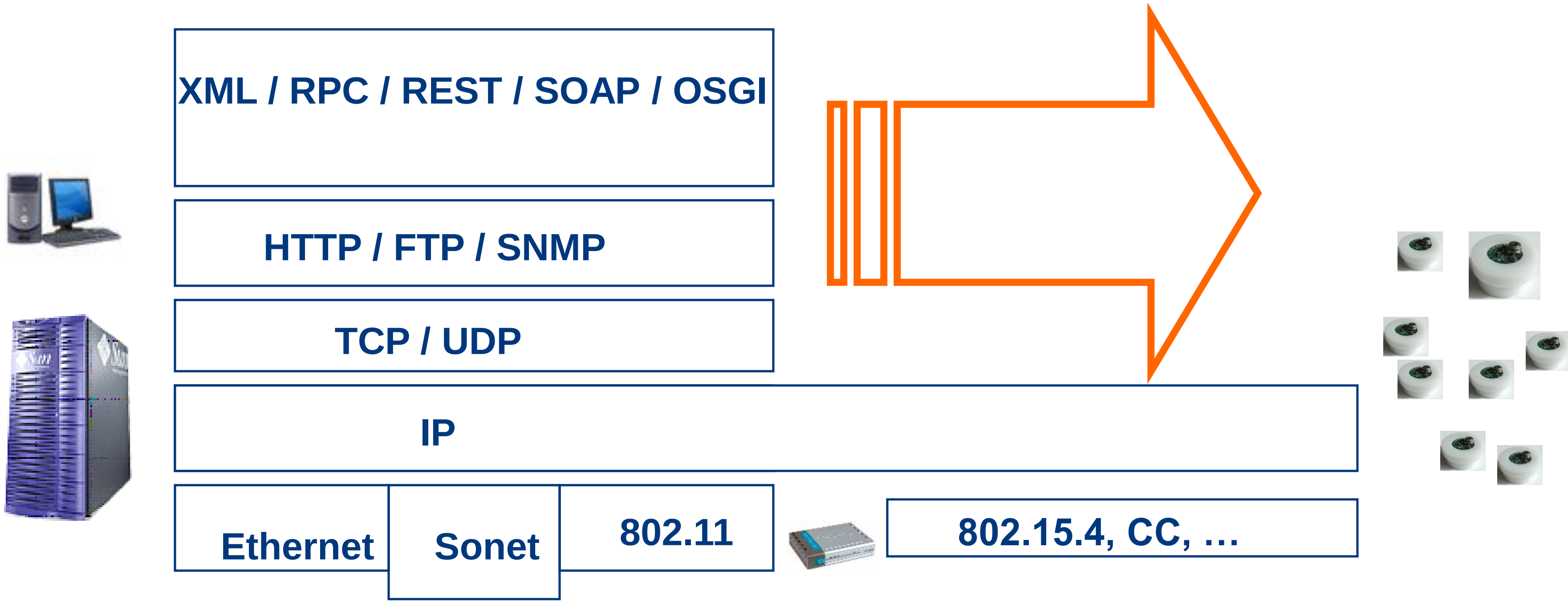
TCP / UDP

IP

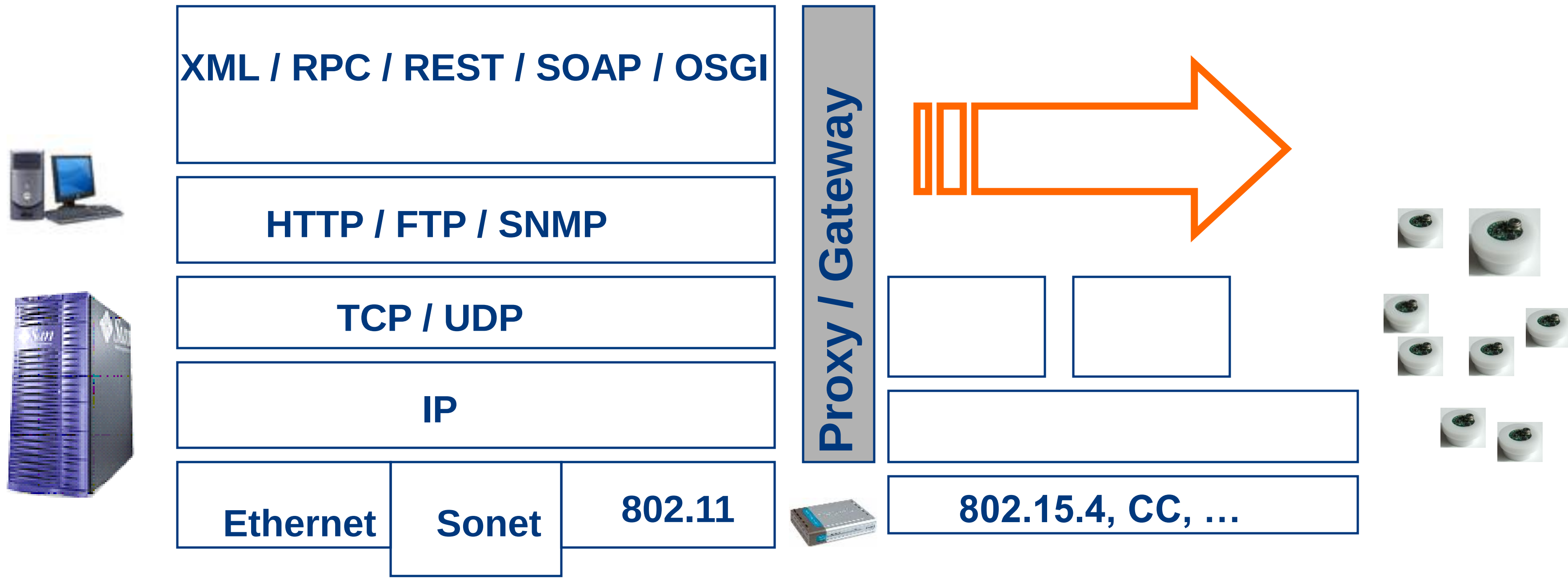
Ethernet	Sonet	802.11

802.15.4, CC, …

Full IP stack throughout



Edge Network Approach

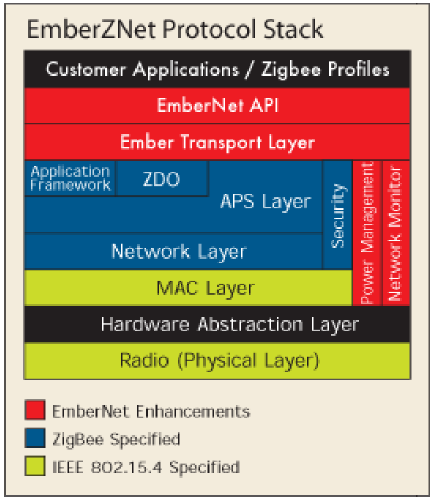


“Hacking it in” may not be so bad

- Security
  – No IP to the nodes, attacks have to get through the gateway or be physically close
- Namespace management
  – Name nodes, networks, services
- Mask intermittent connectivity
  – Terminate IP on the powered side
  – Loosely couple, energy aware protocols on the other
- Distillation proxies
  – Small binary packets where constrained
  – Expanded to full text, XML, HTML, web services
- Mobility, Aggregate communication, …
- Rich suite of networking techniques in the Patch unimpeded by the “ossification” of the core

SensorNets need the Wisdom of the “Internet Architecture”

- Design for change!
- Network protocols must work over a wide variety of links
  - Links will evolve
- Network protocols must work for a variety of applications
  - Applications will evolve
- Provide only simple primitives
  - Don’t confuse the networking standard with a programming methodology
- Don’t try to lock-in your advantage in the spec
- Open process
- Rough consensus AND running code



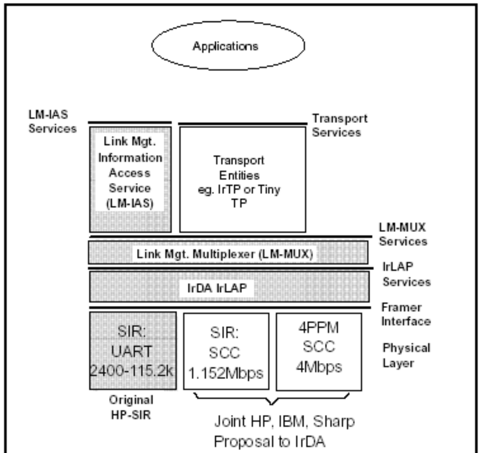


Figure 2.1 IrDA Architecture

Sensor Network "Networking"

ArchRock

Appln

Transport

Routing

Scheduling

Topology

Link

Phy

EnviroTrack
Hood
TinyDB
Regions
FTSP
Diffusion
SPIN
TTDD
Deluge
Trickle
Drip
MMRP
TORA
Ascent
Arrive
CGSR
MintRoute
AODV
DSR
ARA
GSR
GPSR
GRAD
DSDV
DBF
TBRPF
Resynch
SPAN
GAF
FPS
ReORg
PC
Yao
SP100.11a
SMAC
PAMAS
WooMac
TMAC
WiseMAC
Pico
Bluetooth
802.15.4
RadioMetrix
eyes
CC1000
RFM
nordic
Zigbee
WHART
Zwave

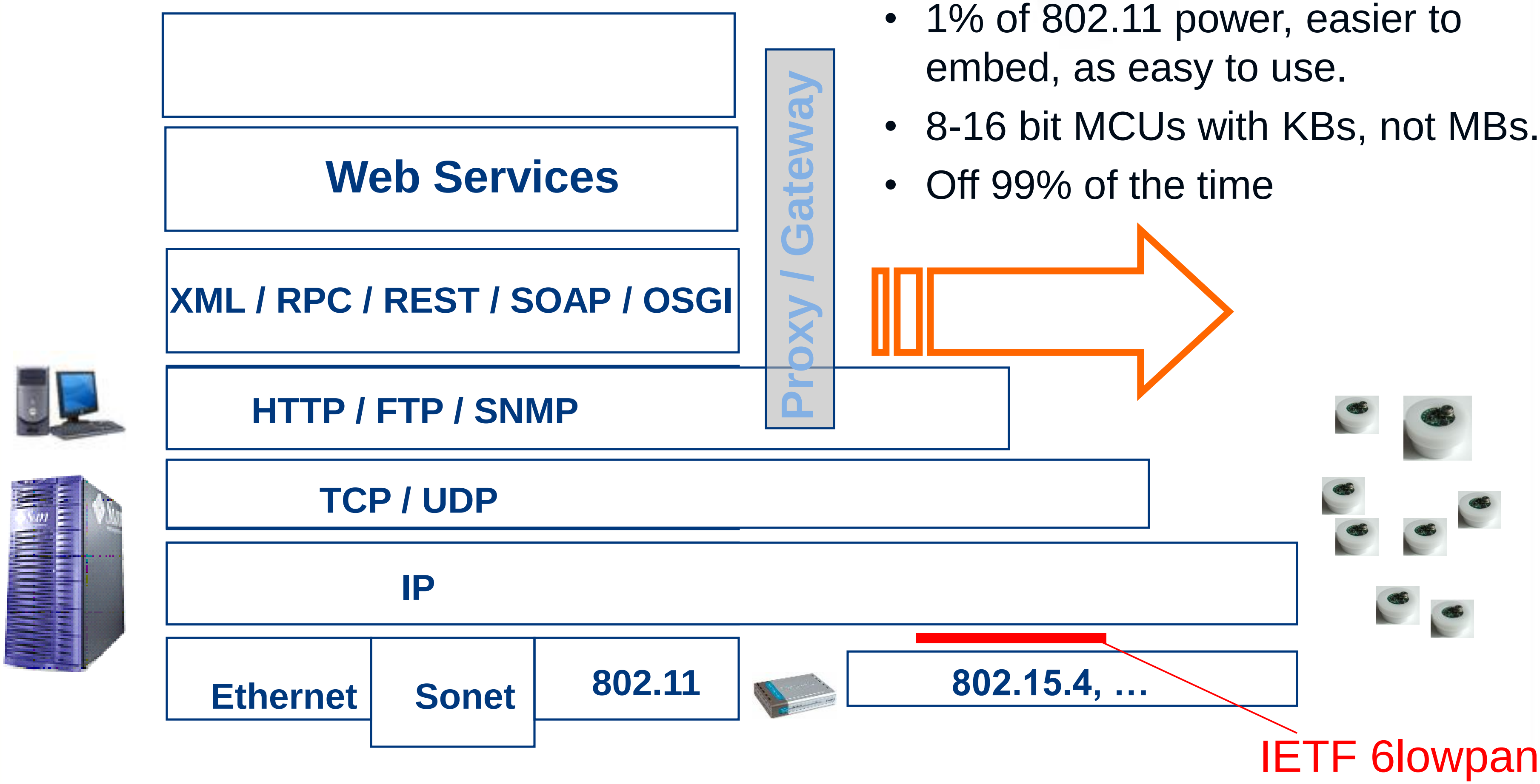
Many Advantages of IP

- **Extensive interoperability**
  - Other wireless embedded 802.15.4 network devices
  - Devices on any other IP network link (WiFi, Ethernet, GPRS, Serial lines, …)
- **Established security**
  - Authentication, access control, and firewall mechanisms
  - Network design and policy determines access, not the technology
- **Established naming, addressing, translation, lookup, discovery**
- **Established proxy architectures for higher-level services**
  - NAT, load balancing, caching, mobility
- **Established application level data model and services**
  - HTTP/HTML/XML/SOAP/REST, Application profiles
- **Established network management tools**
  - Ping, Traceroute, SNMP, … OpenView, NetManager, Ganglia, …
- **Transport protocols**
  - End-to-end reliability in addition to link reliability
- **Most “industrial” (wired and wireless) standards support an IP option**

Making sensor nets make sense

LoWPAN – 802.15.4

- 1% of 802.11 power, easier to embed, as easy to use.
- 8-16 bit MCUs with KBs, not MBs.
- Off 99% of the time



Leverage existing standards, rather than "reinventing the wheel"

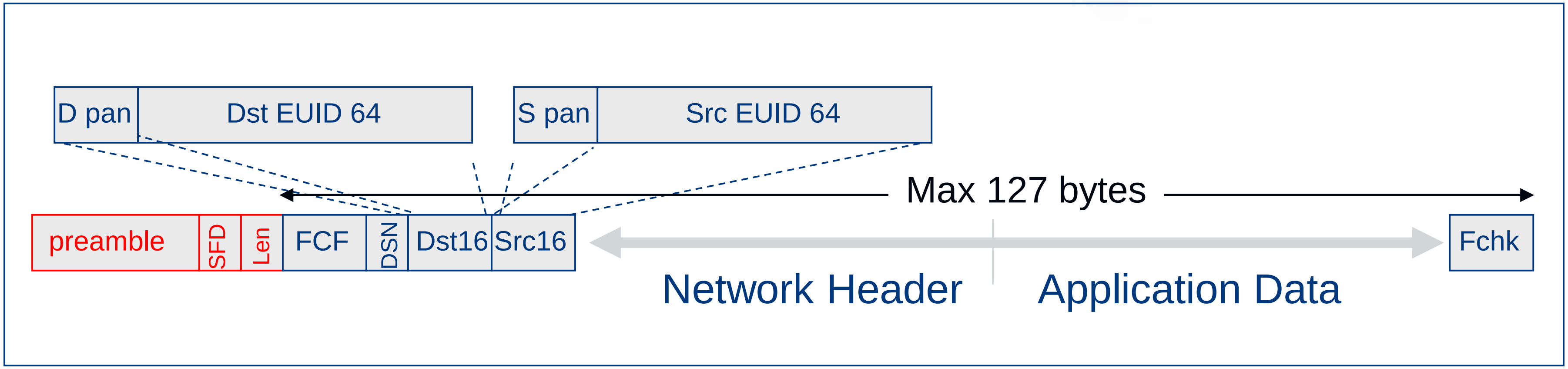
RFC 768	UDP - User Datagram Protocol	[1980]
RFC 791	IPv4 – Internet Protocol	[1981]
RFC 792	ICMPv4 – Internet Control Message Protocol	[1981]
RFC 793	TCP – Transmission Control Protocol	[1981]
RFC 862	Echo Protocol	[1983]
RFC 1101	DNS Encoding of Network Names and Other Types	[1989]
RFC 1191	IPv4 Path MTU Discovery	[1990]
RFC 1981	IPv6 Path MTU Discovery	[1996]
RFC 2131	DHCPv4 - Dynamic Host Configuration Protocol	[1997]
RFC 2375	IPv6 Multicast Address Assignments	[1998]
RFC 2460	IPv6	[1998]
RFC 2463	ICMPv6 - Internet Control Message Protocol for IPv6	[1998]
RFC 2765	Stateless IP/ICMP Translation Algorithm (SIIT)	[2000]
RFC 3068	An Anycast Prefix for 6to4 Relay Routers	[2001]
RFC 3307	Allocation Guidelines for IPv6 Multicast Addresses	[2002]
RFC 3315	DHCPv6 - Dynamic Host Configuration Protocol for IPv6	[2003]
RFC 3484	Default Address Selection for IPv6	[2003]
RFC 3587	IPv6 Global Unicast Address Format	[2003]
RFC 3819	Advice for Internet Subnetwork Designers	[2004]
RFC 4007	IPv6 Scoped Address Architecture	[2005]
RFC 4193	Unique Local IPv6 Unicast Addresses	[2005]
RFC 4291	IPv6 Addressing Architecture	[2006]

- **Proposed Standard - "Transmission of IPv6 Packets over IEEE 802.15.4 Networks"**

Key Factors for IP over 802.15.4

- Header
  - Standard IPv6 header is 40 bytes [RFC 2460]
  - Entire 802.15.4 MTU is 127 bytes [IEEE]
  - Often data payload is small
- Fragmentation
  - Interoperability means that applications need not know the constraints of physical links that might carry their packets
  - IP packets may be large, compared to 802.15.4 max frame size
  - IPv6 requires all links support 1280 byte packets [RFC 2460]
- Allow link-layer mesh routing under IP topology
  - 802.15.4 subnets may utilize multiple radio hops per IP hop
  - Similar to LAN switching within IP routing domain in Ethernet
- Allow IP routing over a mesh of 802.15.4 nodes
  - Options and capabilities already well-defines
  - Various protocols to establish routing tables
- Energy calculations and 6LoWPAN impact

IEEE 802.15.4 Frame Format



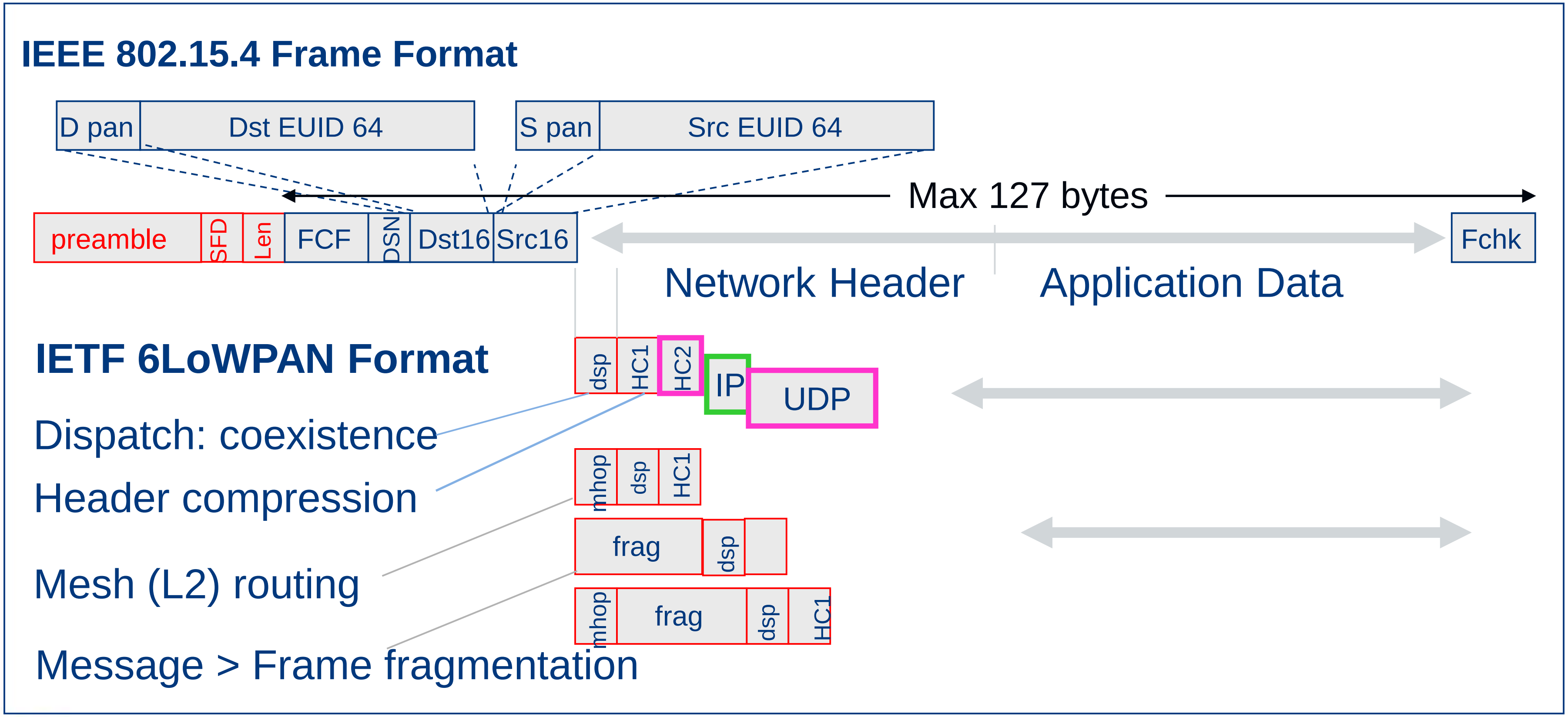
- Low Bandwidth (250 kbps), low power (1 mW) radio
- Moderately spread spectrum (QPSK) provides robustness
- Simple MAC allows for general use
  - Many TinyOS-based protocols (MintRoute, LQI, BVR, …), TinyAODV, Zigbee, SP100.11, Wireless HART, …
  - 6LoWPAN => IP
- Choice among many semiconductor suppliers
- Small Packets to keep packet error rate low and permit media sharing

RFC 3189 – "Advice for Internet Sub-Network Designers"

- Total end-to-end interactive response time should not exceed human perceivable delays
- Lack of broadcast capability impedes or, in some cases, renders some protocols inoperable (e.g. DHCP). Broadcast media can also allow efficient operation of multicast, a core mechanism of IPv6
- Link-layer error recovery often increases end-to-end performance. However, it should be lightweight and need not be perfect, only good enough
- Sub-network designers should minimize delay, delay variance, and packet loss as much as possible
- Sub-networks operating at low speeds or with small MTUs should compress IP and transport-level headers (TCP and UDP)

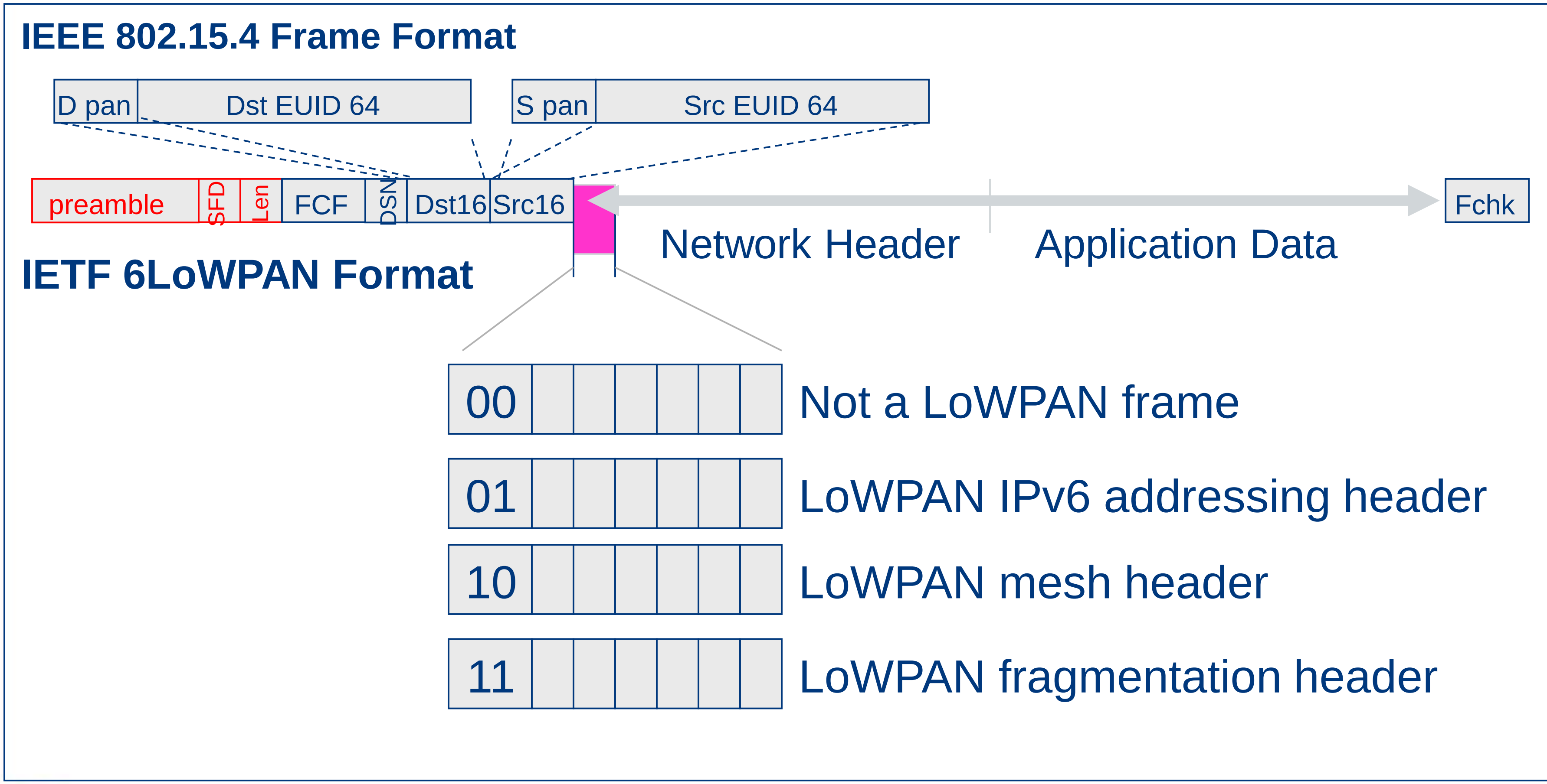
6LoWPAN Format Design

- Orthogonal stackable header format
- Almost no overhead for the ability to interoperate and scale.
- Pay for only what you use



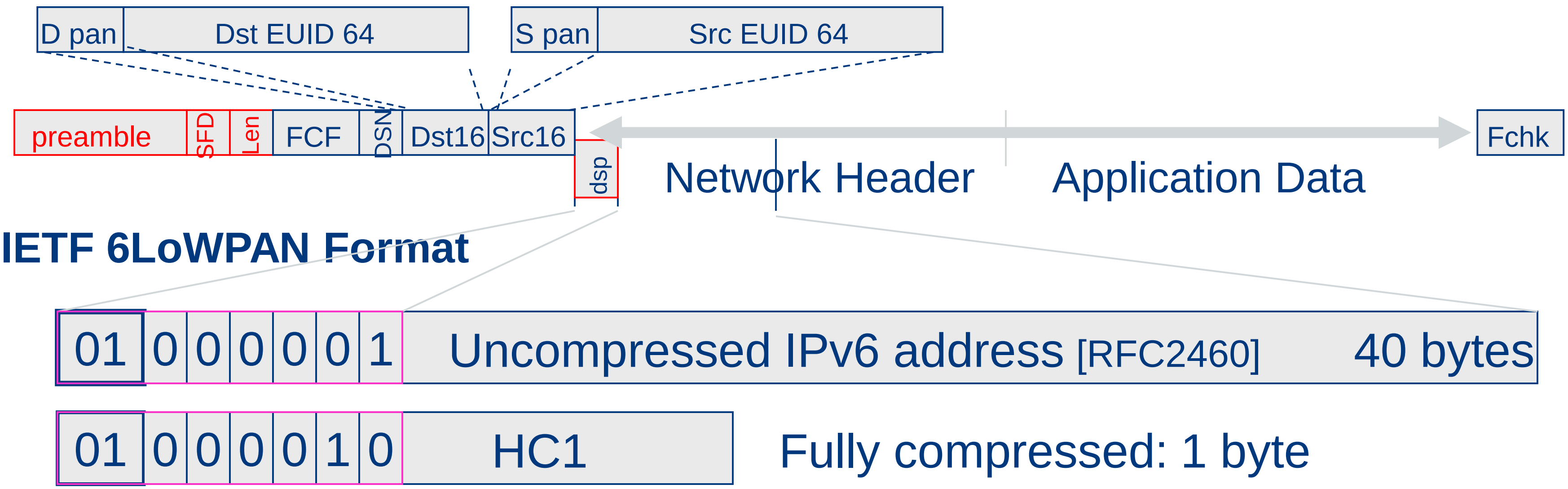
6LoWPAN – The First Byte

- Coexistence with other network protocols over same link
- Header dispatch - understand what's coming



6LoWPAN – IPv6 Header

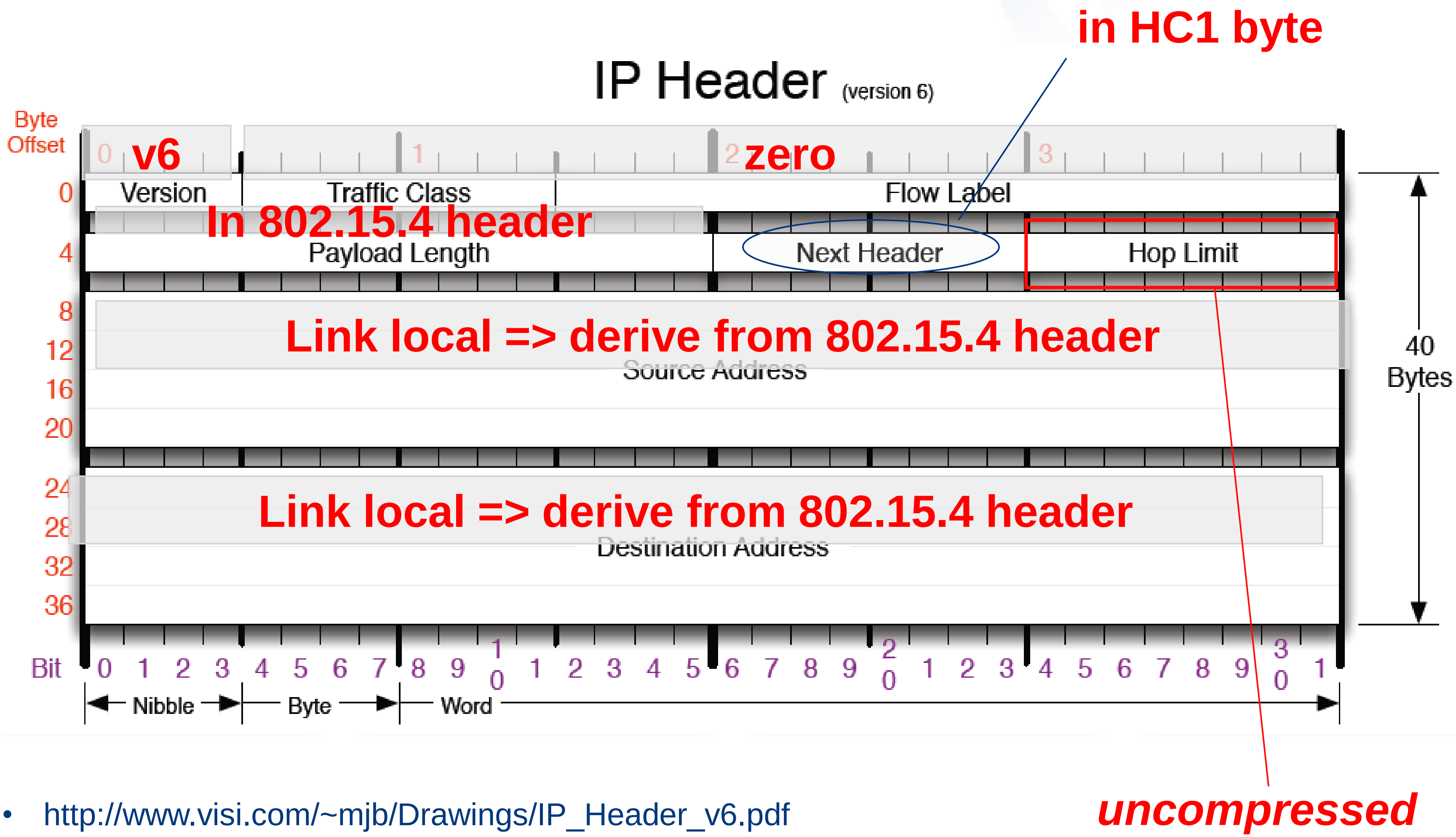
IEEE 802.15.4 Frame Format



IETF 6LoWPAN Format

Source address	: derived from link address
Destination address	: derived from link address
Traffic Class & Flow Label	: zero
Next header	: UDP, TCP, or ICMP

IPv6 Header Compression



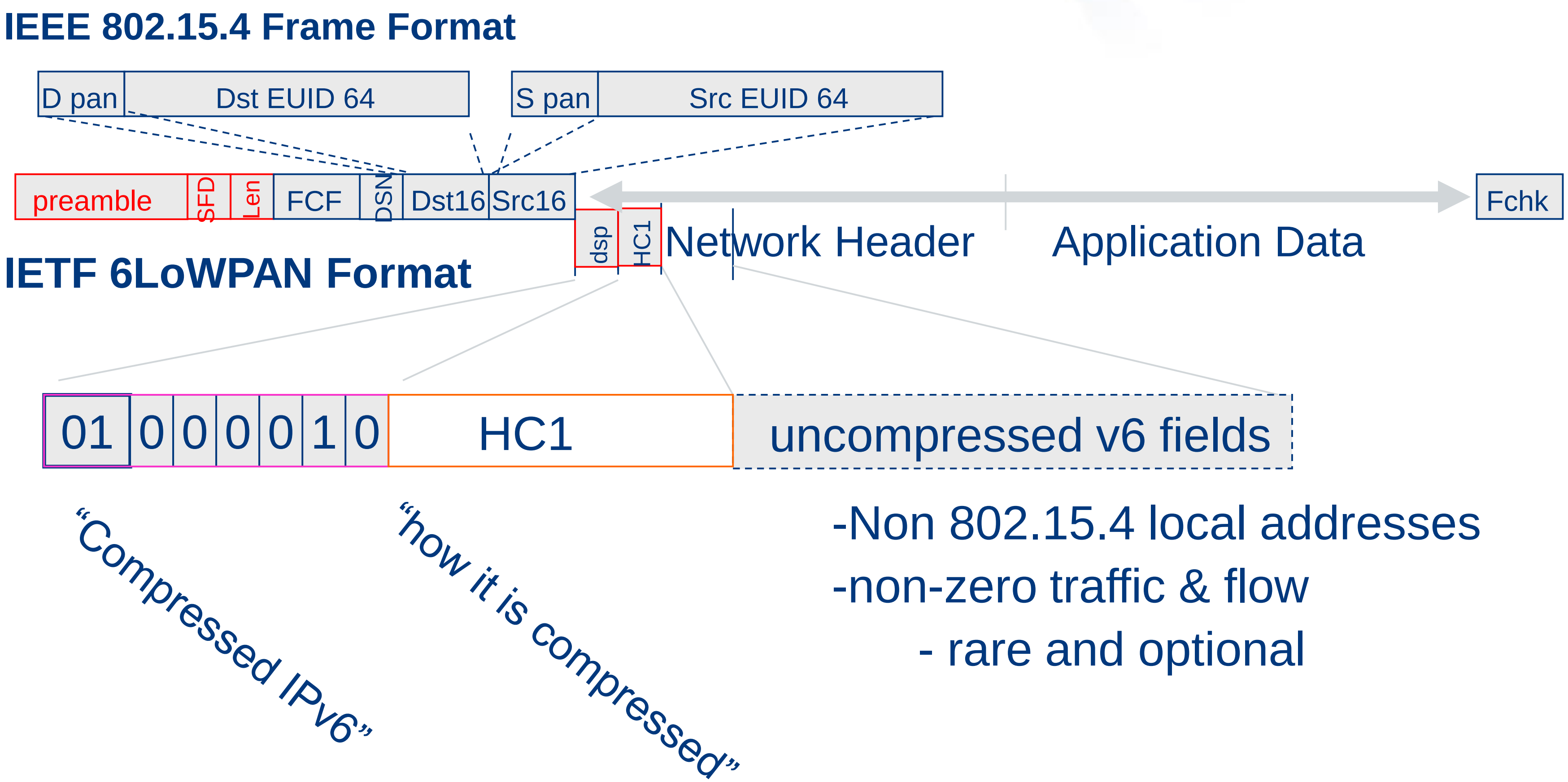
- http://www.visi.com/~mjb/Drawings/IP_Header_v6.pdf

HC1 Compressed IPv6 Header

- Source prefix compressed (to L2)
- Source interface identifier compressed (to L2)
- Destination prefix compressed (to L2)
- Destination interface identified compressed (to L2)
- Traffic and Flow Label zero (compressed)
- Next Header
  - 00 uncompressed, 01 UDP, 10 TCP, 11 ICMP
- Additional HC2 compression header follows

- IPv6 address <prefix64 || interface id> for nodes in 802.15.4 subnet derived from the link address.
  – PAN ID maps to a unique IPv6 prefix
  – Interface identifier generated from EUID64 or Pan ID & short address
- Hop Limit is the only incompressible IPv6 header field

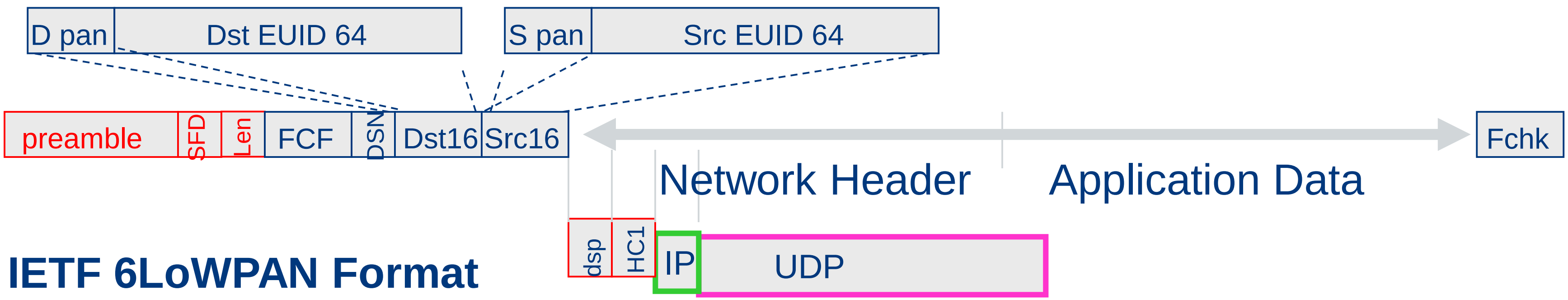
6LoWPAN: Compressed IPv6 Header



-Non 802.15.4 local addresses
-non-zero traffic & flow
- rare and optional

6LoWPAN – Compressed / UDP

IEEE 802.15.4 Frame Format

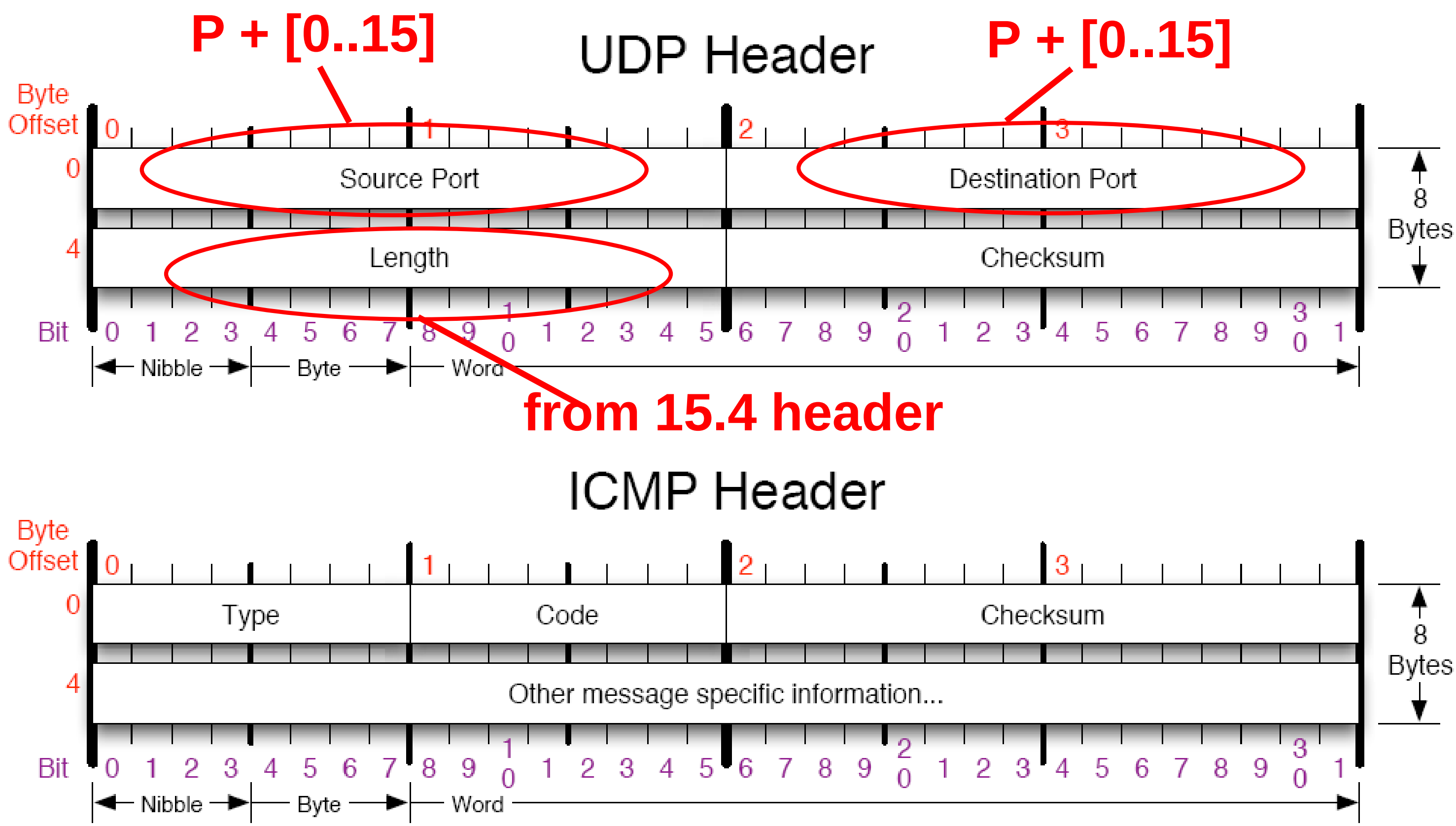


IETF 6LoWPAN Format

Dispatch: Compressed IPv6

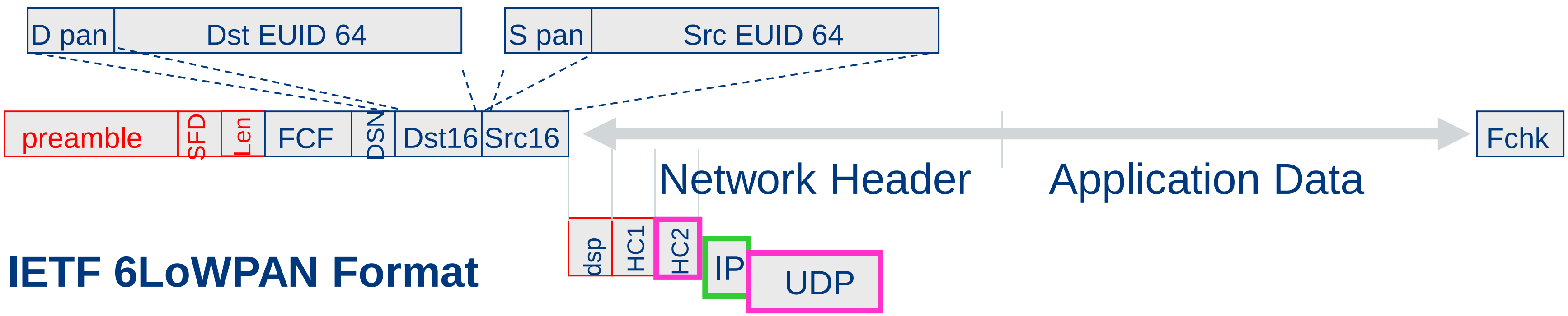
HC1: Source & Dest Local, next hdr=UDP
IP: Hop limit
UDP: 8-byte header (uncompressed)

L4 – UDP/ICMP Headers (8 bytes)



6LoWPAN – Compressed / Compressed UDP

IEEE 802.15.4 Frame Format



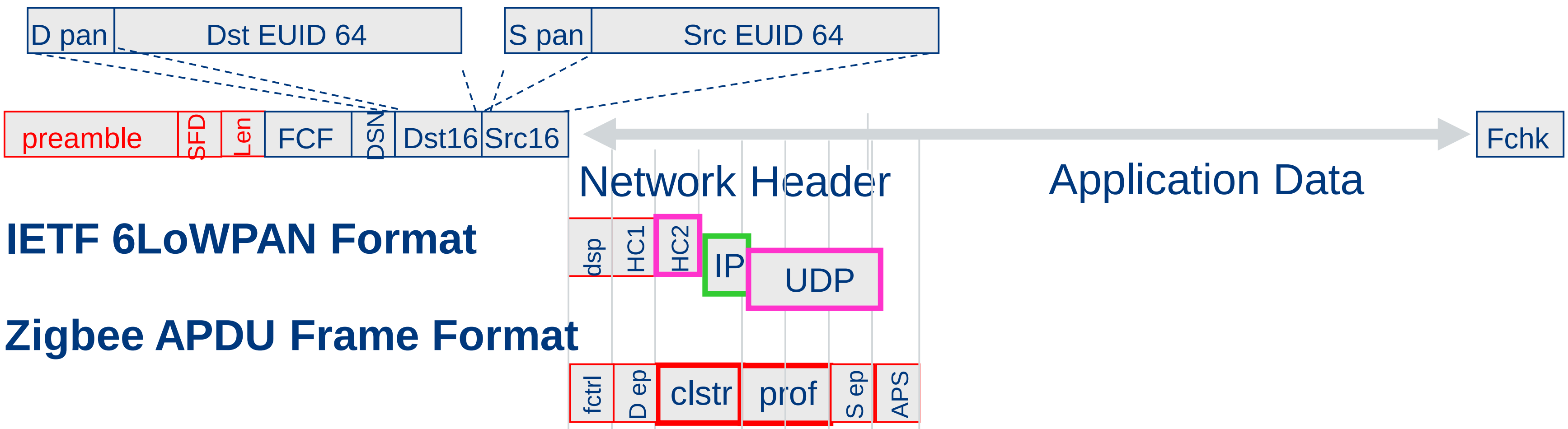
IETF 6LoWPAN Format

Dispatch: Compressed IPv6

HC1: Source & Dest Local, next hdr=UDP
IP: Hop limit
UDP: HC2+3-byte header (compressed)
source port = P + 4 bits, p = 61616 (0xF0B0)
destination port = P + 4 bits

6LoWPAN / Zigbee Comparison

IEEE 802.15.4 Frame Format

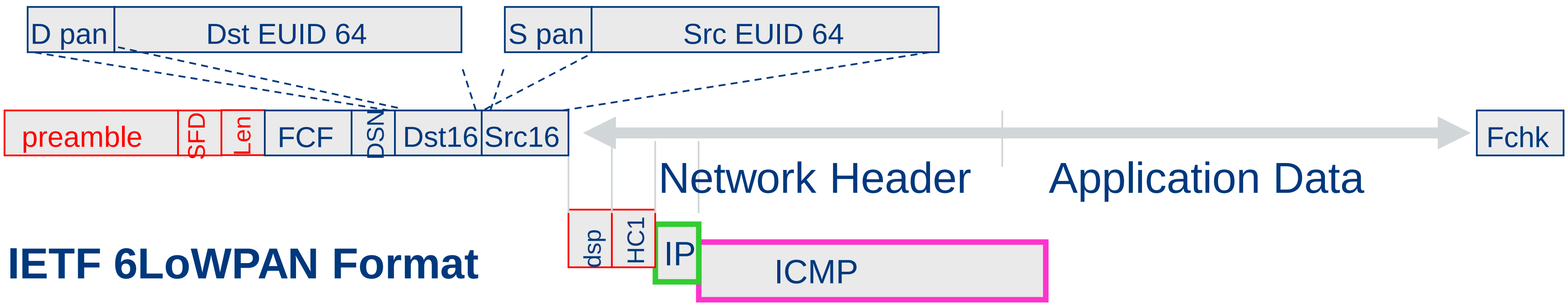


fctrl:	Frame Control bit fields
D ep:	Destination Endpoint (like UDP port)
clstr:	cluster identifier
prof:	profile identifier
S ep:	Source Endpoint
APS:	APS counter (sequence to prevent duplicates)

*** Typical configuration. Larger and smaller alternative forms exist.

6LoWPAN – Compressed / ICMP

IEEE 802.15.4 Frame Format



IETF 6LoWPAN Format

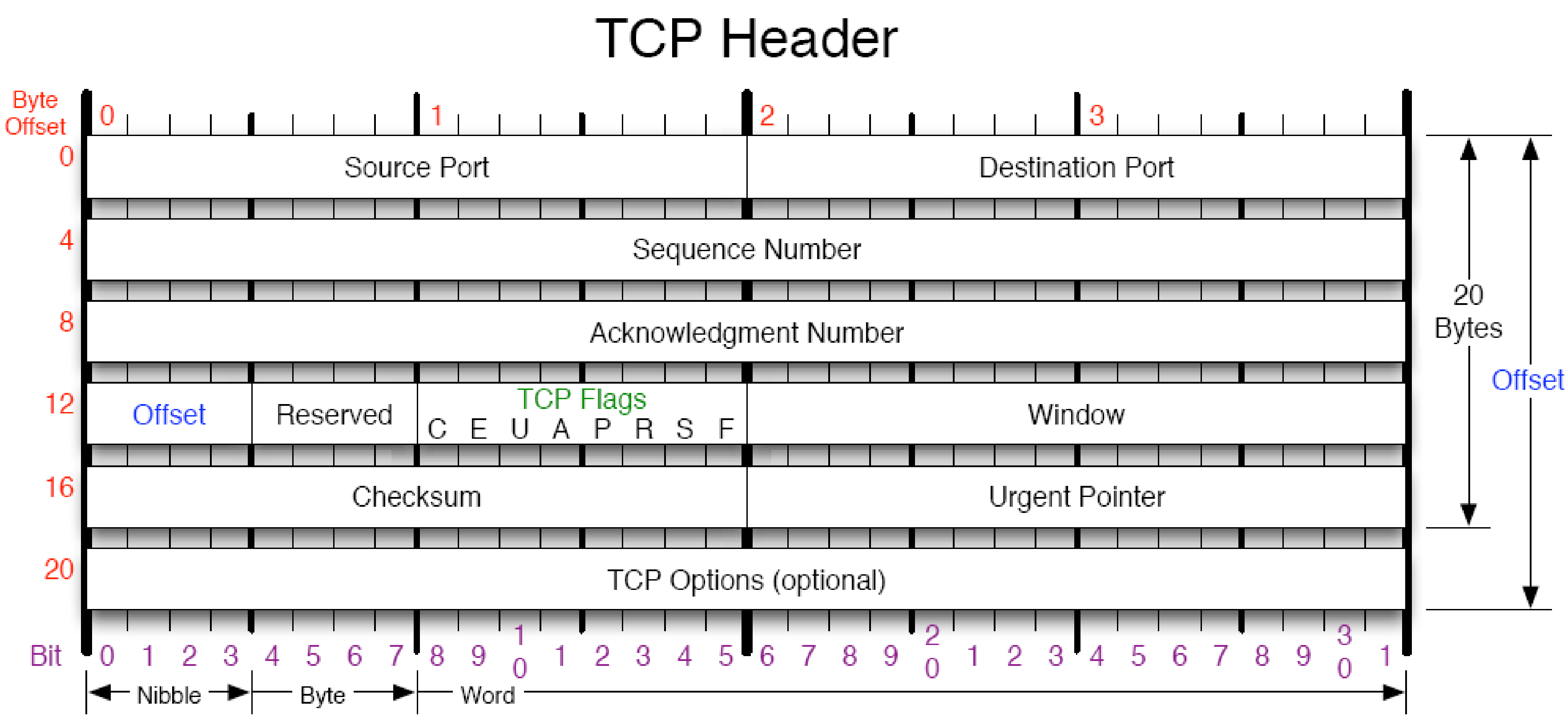
Dispatch: Compressed IPv6

HC1: Source & Dest Local, next hdr=ICMP

IP: Hops Limit

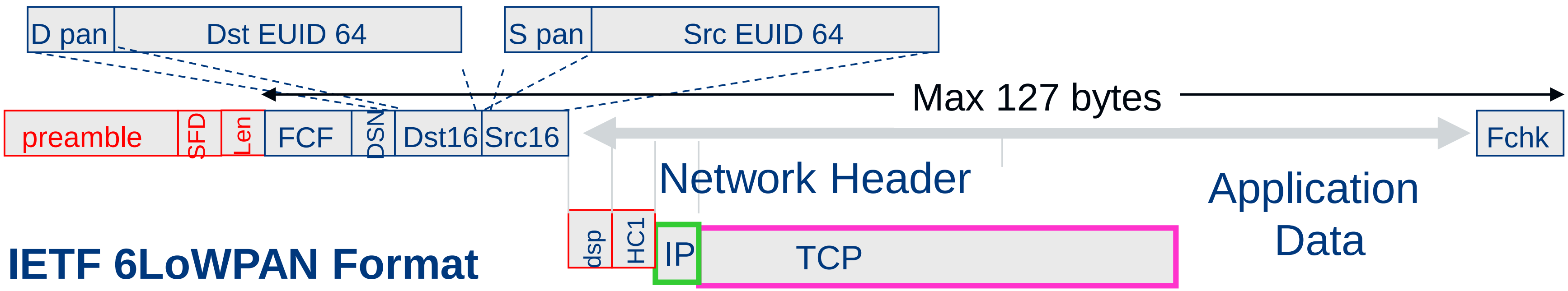
ICMP: 8-byte header

L4 – TCP Header (20 bytes)



6LoWPAN – Compressed / TCP

IEEE 802.15.4 Frame Format



IETF 6LoWPAN Format

Dispatch: Compressed IPv6

HC1: Source & Dest Local, next hdr=TCP
IP: Hops Limit
TCP: 20-byte header

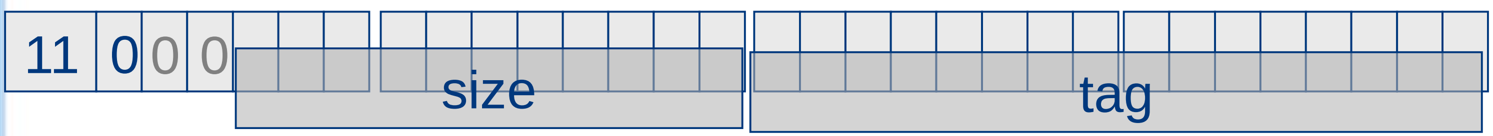
Key Points for IP over 802.15.4

- Header overhead
  - Standard IPv6 header is 40 bytes [RFC 2460]
  - Entire 802.15.4 MTU is 127 bytes [IEEE std]
  - Often data payload is small
- Fragmentation
  - Interoperability means that applications need not know the constraints of physical links that might carry their packets
  - IP packets may be large, compared to 802.15.4 max frame size
  - IPv6 requires all links support 1280 byte packets [RFC 2460]
- Allow link-layer mesh routing under IP topology
  - 802.15.4 subnets may utilize multiple radio hops per IP hop
  - Similar to LAN switching within IP routing domain in Ethernet
- Allow IP routing over a mesh of 802.15.4 nodes
  - Localized internet of overlapping subnets
- Energy calculations and 6LoWPAN impact

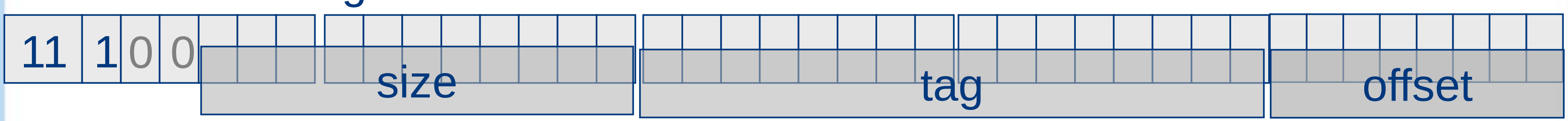
Fragmentation

- All fragments of an IP packet carry the same “tag”
  - Assigned sequentially at source of fragmentation
- Each specifies tag, size, and position
- Do not have to arrive in order
- Time limit for entire set of fragments (60s)

First fragment

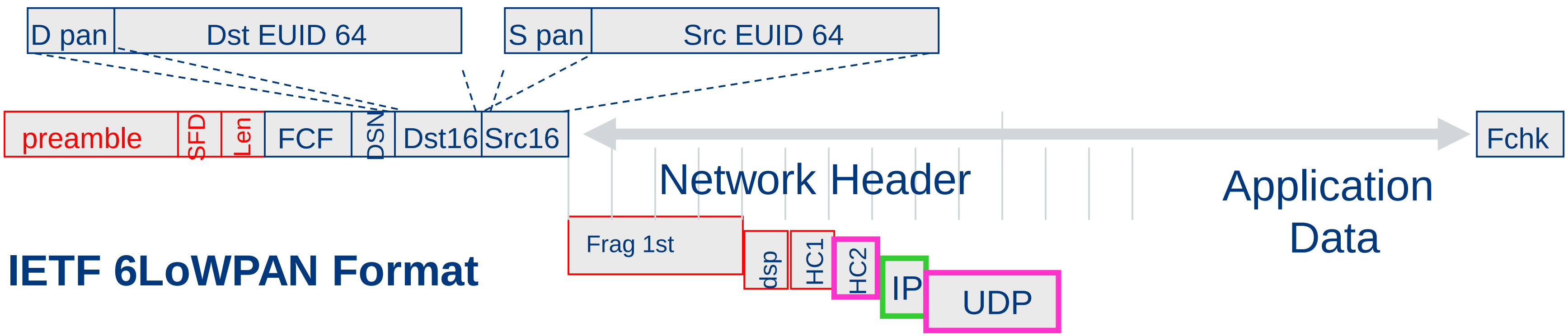


Rest of the fragments



6LoWPAN – Example
Fragmented / Compressed / Compressed UDP

IEEE 802.15.4 Frame Format



Dispatch: Fragmented, First Fragment, Tag, Size

Dispatch: Compressed IPv6

HC1: Source & Dest Local, next hdr=UDP
IP: Hop limit
UDP: HC2+3-byte header (compressed)

Key Points for IP over 802.15.4

- Header overhead
  - Standard IPv6 header is 40 bytes [RFC 2460]
  - Entire 802.15.4 MTU is 127 bytes [IEEE std]
  - Often data payload is small
- Fragmentation
  - Interoperability means that applications need not know the constraints of physical links that might carry their packets
  - IP packets may be large, compared to 802.15.4 max frame size
  - IPv6 requires all links support 1280 byte packets [RFC 2460]
- Allow link-layer mesh routing under IP topology
  - 802.15.4 subnets may utilize multiple radio hops per IP hop
  - Similar to LAN switching within IP routing domain in Ethernet
- Allow IP routing over a mesh of 802.15.4 nodes
  - Localized internet of overlapping subnets
- Energy calculations and 6LoWPAN impact

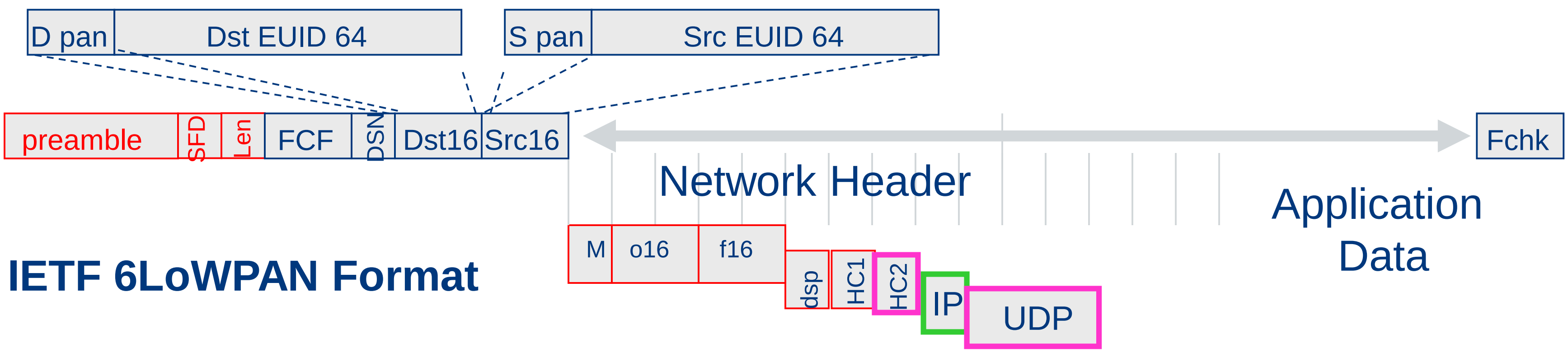
“Mesh Under” Header

- Originating node and Final node specified by either short (16 bit) or EUID (64 bit) 802.15.4 address
  - In addition to IP source and destination
- Hops Left (up to 14 hops, then add byte)
- Mesh protocol determines node at each mesh hop

LoWPAN mesh header

6LoWPAN – Example
Mesh / Compressed / Compressed UDP

IEEE 802.15.4 Frame Format



IETF 6LoWPAN Format

Dispatch: Mesh under, orig short, final short

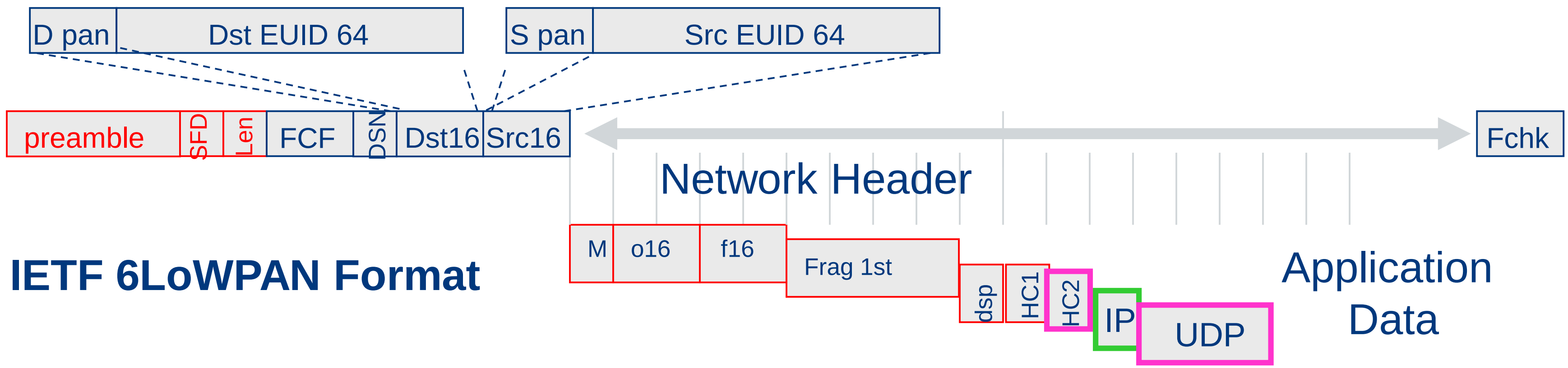
Mesh: orig addr, final addr

Dispatch: Compressed IPv6

HC1: Source & Dest Local, next hdr=UDP
IP: Hop limit
UDP: HC2+3-byte header

6LoWPAN – Example
Mesh / Fragmented / Compressed / UDP

IEEE 802.15.4 Frame Format



Dispatch: Mesh under, orig short, final short

Mesh: orig addr, final addr

Dispatch: Fragmented, First Fragment, Tag, Size

Dispatch: Compressed IPv6

HC1: Source & Dest Local, next hdr=UDP
IP: Hop limit
UDP: HC2 + 3-byte header

Key Points for IP over 802.15.4

- Header overhead
  - Standard IPv6 header is 40 bytes [RFC 2460]
  - Entire 802.15.4 MTU is 127 bytes [IEEE std]
  - Often data payload is small
- Fragmentation
  - Interoperability means that applications need not know the constraints of physical links that might carry their packets
  - IP packets may be large, compared to 802.15.4 max frame size
  - IPv6 requires all links support 1280 byte packets [RFC 2460]
- Allow link-layer mesh routing under IP topology
  - 802.15.4 subnets may utilize multiple radio hops per IP hop
  - Similar to LAN switching within IP routing domain in Ethernet
- Allow IP routing over a mesh of 802.15.4 nodes
  - Localized internet of overlapping subnets
- Energy calculations and 6LoWPAN impact

IP-Based Multi-Hop Routing

- IP has always done "multi-hop"
  - Routers connect sub-networks to one another
  - The sub-networks may be the same or different physical links
- Routers utilize routing tables to determine which node represents the "next hop" toward the destination
- Routing protocols establish and maintain proper routing tables
  - Routers exchange messages using more basic communication capabilities
  - Different routing protocols are used in different situations
  - RIP, OSPF, IGP, BGP, AODV, OLSR, …
- IP routing over 6LoWPAN links does not require additional header information at 6LoWPAN layer

IPv6 Address Auto-Configuration

64-bit Prefix

64-bit Suffix or
Interface Identifier

Link Local

EUID - 64

pan* | 00-FF-FE-00 | short

802.15.4
Address

PAN* - complement the “Universal/Local" (U/L) bit, which is the next-to-lowest order bit of the first octet

Key Points for IP over 802.15.4

- Header overhead
  - Standard IPv6 header is 40 bytes [RFC 2460]
  - Entire 802.15.4 MTU is 127 bytes [IEEE std]
  - Often data payload is small
- Fragmentation
  - Interoperability means that applications need not know the constraints of physical links that might carry their packets
  - IP packets may be large, compared to 802.15.4 max frame size
  - IPv6 requires all links support 1280 byte packets [RFC 2460]
- Allow link-layer mesh routing under IP topology
  - 802.15.4 subnets may utilize multiple radio hops per IP hop
  - Similar to LAN switching within IP routing domain in Ethernet
- Allow IP routing over a mesh of 802.15.4 nodes
  - Localized internet of overlapping subnets
- Energy calculations and 6LoWPAN impact

Energy Efficiency

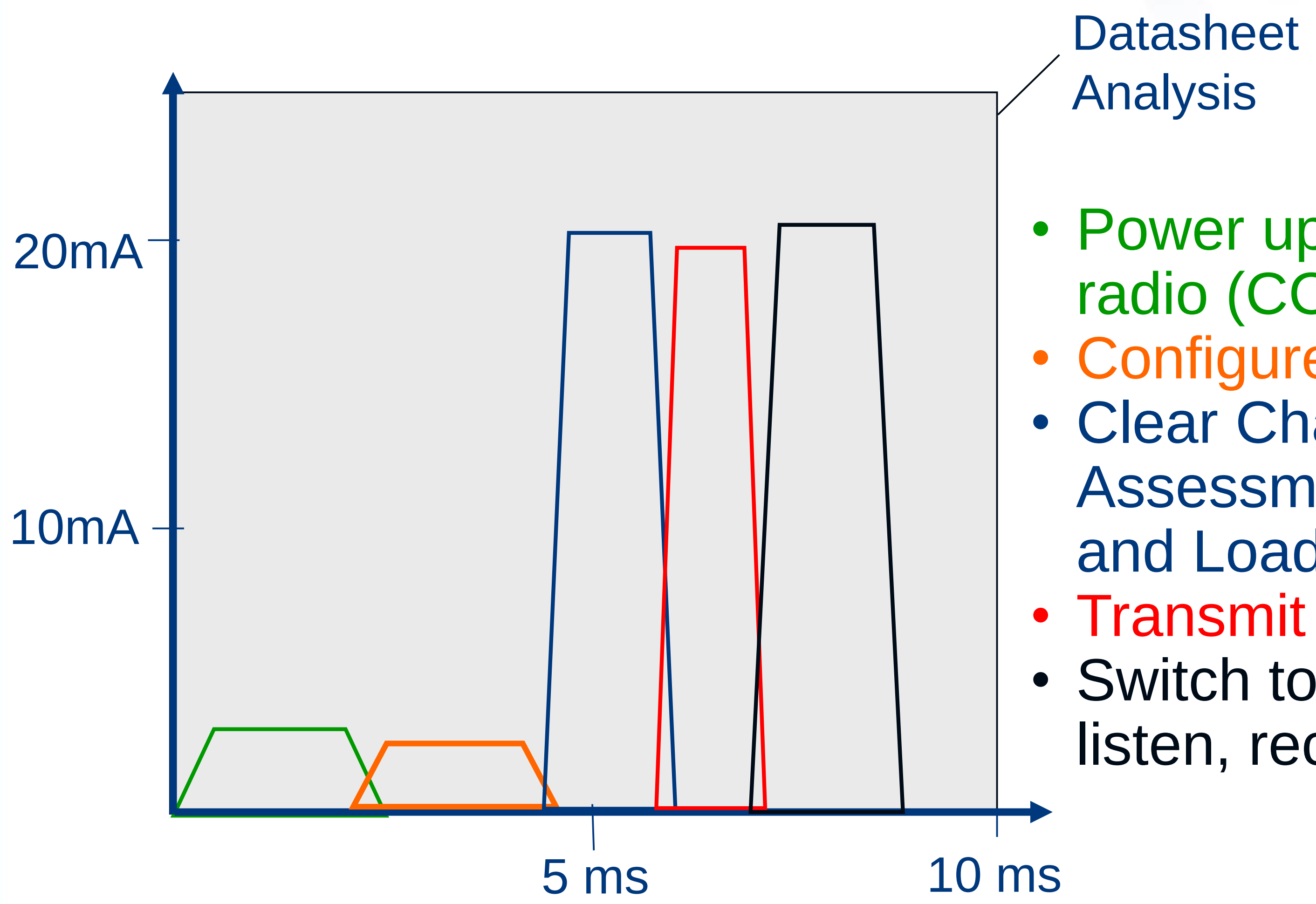
- Battery capacity typically rated in Amp-hours
  - Chemistry determines voltage
  - AA Alkaline: ~2,000 mAh = 7,200,000 mAs
  - D Alkaline: ~15,000 mAh = 54,000,000 mAs
- Unit of effort: mAs
  - multiply by voltage to get energy (joules)
- Lifetime
  - 1 year = 31,536,000 secs

  $\Rightarrow$ 228 uA average current on AA

  $\Rightarrow$ 72,000,000 packets TX or Rcv @ 100 uAs per TX or Rcv

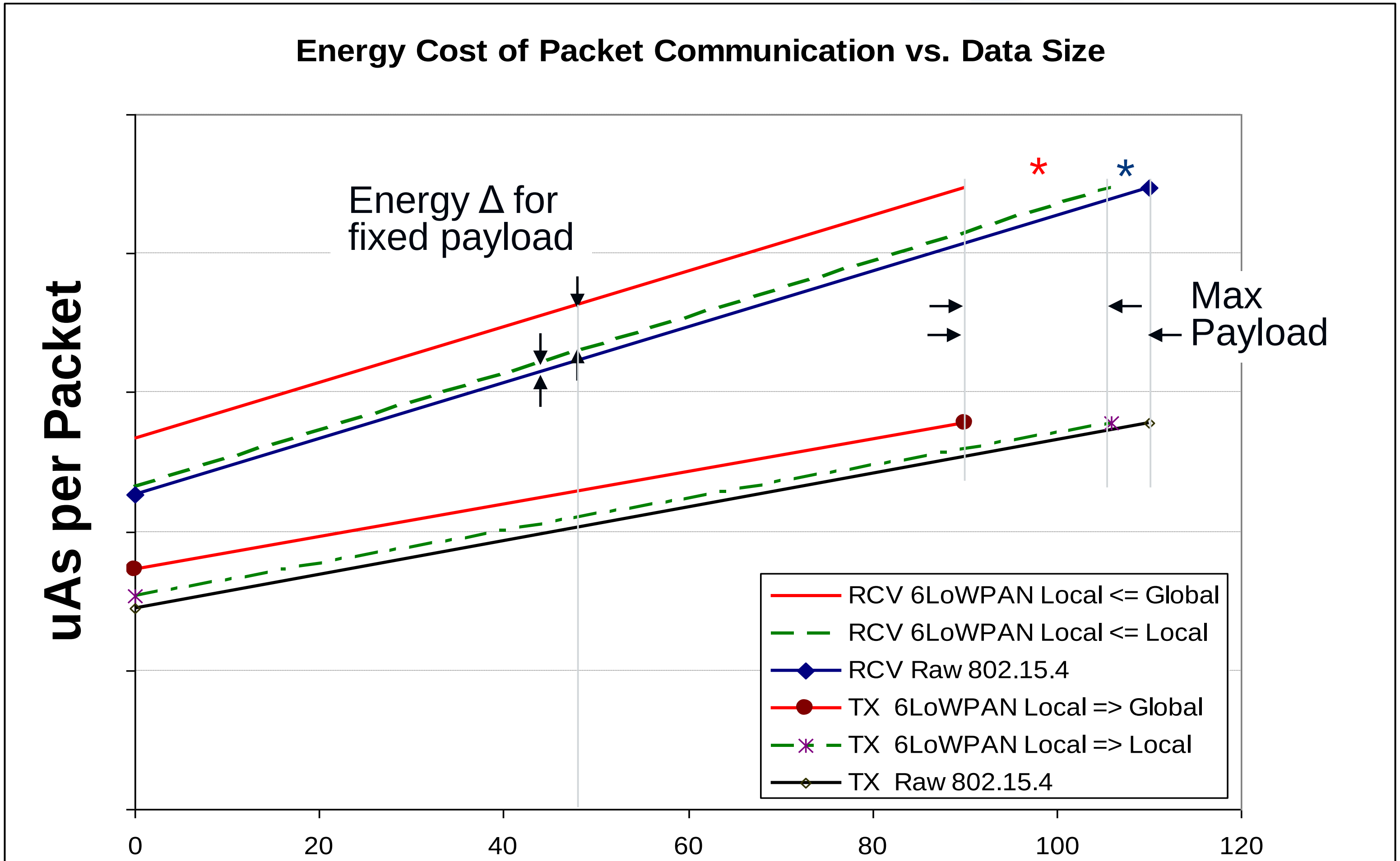
  $\Rightarrow$ 2 packets per second for 1 year if no other consumption

Energy Profile of a Transmission



- Power up oscillator & radio (CC2420)
- Configure radio
- Clear Channel Assessment, Encrypt and Load TX buffer
- Transmit packet
- Switch to rcv mode, listen, receive ACK

Low Impact of 6LoWPAN on Lifetime – Comparison to *Raw* 802.15.4 Frame



* fully compressed header

* additional 16-byte IPv6 address

Rest of the Energy Story

- Energy cost of communication has four parts
  - Transmission
  - Receiving
  - Listening (staying ready to receive)
  - Overhearing (packets destined for others)
- The increase in header size to support IP over 802.15.4 results in a small increase in transmit and receive costs
  - Both infrequent in long term monitoring
- The dominant cost is listening! – regardless of format.
  - Can only receive if transmission happens when radio is on, “listening”
  - Critical factor is not collisions or contention, but when and how to listen
  - Preamble sampling, low-power listening and related listen “all the time” in short gulps and pay extra on transmission
  - TDMA, FPS, TSMP and related communication scheduling listen only now and then in long gulps. Transmission must wait for listen slot. Clocks must be synchronized. Increase delay to reduce energy consumption.

Conclusion

- 6LoWPAN turns IEEE 802.15.4 into the next IP-enabled link
- Provides open-systems based interoperability among low-power devices over IEEE 802.15.4
- Provides interoperability between low-power devices and existing IP devices, using standard routing techniques
- Paves the way for further standardization of communication functions among low-power IEEE 802.15.4 devices
- Offers watershed leverage of a huge body of IP-based operations, management and communication services and tools
- Great ability to work within the resource constraints of low-power, low-memory, low-bandwidth devices like WSN

Frequently Asked Questions

How does 6LoWPAN compare to Zigbee, SP100.11a, …?

- Zigbee
  - only defines communication between 15.4 nodes ("layer 2" in IP terms), not the rest of the network (other links, other nodes).
  - defines new upper layers, all the way to the application, similar to IRDA, USB, and Bluetooth, rather utilizing existing standards.
  - Specification still in progress (Zigbee 2006 incompatible with Zigbee 1.0. Zigbee 2007 in progress.) Lacks a transport layer.
- SP100.11a
  - seeks to address a variety of links, including 15.4, 802.11, WiMax, and future "narrow band frequency hoppers".
  - Specification is still in the early stages, but it would seem to need to redefine much of what is already defined with IP.
  - Much of the emphasis is on the low-level media arbitration using TDMA techniques (like token ring) rather than CSMA (like ethernet and wifi). This issue is orthogonal to the frame format.
- 6LoWPAN defines how established IP networking layers utilize the 15.4 link.
  - it enables 15.4 ⇔15.4 and 15.4 ⇔non-15.4 communication
  - It enables the use of a broad body of existing standards as well as higher level protocols, software, and tools.
  - It is a focused extension to the suite of IP technologies that enables the use of a new class of devices in a familiar manner.

Do I need IP for my stand-alone network?

- Today, essentially all computing devices use IP network stacks to communicate with other devices, whether they form an isolated stand-alone network, a privately accessible portion of a larger enterprise, or publicly accessible hosts.
  - When all the devices form a subnet, no routing is required, but everything works in just the same way.
- The software, the tools, and the standards utilize IP and the layers above it, not the particular physical link underneath.
- The value of making it “all the same” far outweighs the moderate overheads.
- 6LoWPAN eliminates the overhead where it matters most.

Will the "ease of access" with IP mean less security?

- No.
- The most highly sensitive networks use IP internally, but are completely disconnected from all other computers.
- IP networks in all sorts of highly valued settings are protected by establishing very narrow, carefully managed points of interconnection.
  - Firewalls, DMZs, access control lists, …
- Non-IP nodes behind a gateway that is on a network are no more secure than the gateway device. And those devices are typically numerous, and use less than state-of-the-art security technology.
- 802.15.4 provides built-in AES128 encryption which is enabled beneath IP, much like WPA on 802.11.

Does using 6LoWPAN mean giving up deterministic timing behavior?

- No.
- Use of the 6LoWPAN format for carrying traffic over 802.15.4 links is orthogonal to whether those links are scheduled deterministically.
  - Deterministic media access control (MAC) can be implemented as easily with 6LoWPAN as with any other format.
- There is a long history of such TDMA mechanisms with IP, including Token Ring and FDDI.
  - MAC protocols, such as FPS and TSMP, extend this to a mesh.
  - Ultimately, determinacy requires load limits and sufficient headroom to cover potential losses.
  - Devices using different MACs on the same link (TDMA vs CSMA) may not be able to communicate, even though the packet formats are the same.

Is 6LoWPAN less energy efficient than proprietary protocols?

- No.
- Other protocols carry similar header information for addressing and routing, but in a more ad hoc fashion.
- While IP requires that the general case must work, it permits extensive optimization for specific cases.
- 6LoWPAN optimizes within the low-power 802.15.4 subnet
  - More costly only when you go beyond that link.
  - Other protocols must provide analogous information (at application level) to instruct gateways.
- Ultimately, the performance is determined by the quality the implementation.
  - With IP's open standards, companies must compete on performance and efficiency, rather than proprietary "lock in"

Do I need to run IPv6 instead of IPv4 on the rest of my network to use 6LoWPAN?

- No.
- IPv6 and IPv4 work together throughout the world using 4-6 translation.
- IPv6 is designed to support “billions” of non-traditional networked devices and is a cleaner design.
  - Actually easier to support on small devices, despite the larger addresses.
- The embedded 802.15.4 devices can speak IPv6 with the routers to the rest of the network providing 4-6 translation.
  - Such translation is already standardized and widely available.

Lesson 1: IP

- Separate the logical communication of information from the physical links that carry the packets.
  - Naming
    - Hostname => IP address => Physical MAC
  - Routing
  - Security